The Spectrum, Structure and Interactions of Hadrons

J.W. Negele

DOE Review of the LQCD Computing Project

June 4-5, 2009

Office of Science
U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

SciDAC
Scientific Discovery through Advanced Computing

ASCR

ADVANCED SIMULATION & COMPUTING

INCITE
Advancing America's Science and Industrial Competitiveness

GOALS

- Understanding the structure, spectroscopy and interactions of hadrons from QCD is a central challenge of nuclear physics
- How does the quark and gluon structure of the nucleon arise from QCD?
- What are the effective degrees of freedom manifested in the low-energy spectrum of the theory?
- How do we understand nucleon-nucleon and hadron-hadron interactions from QCD?

View from the Nuclear Physics Long Range Plan

- Quantum Chromodyamics: From the Structure of Hadons to the Phases of Nuclear matter
  - What is the internal landscape of the nucleons?
  - What governs the transition of quarks and gluons into pions and nucleons?
  - What is the role of gluons and gluon self-interactions in nucleons and nuclei?
- QCD and the Structure of Hadrons
  - The distribution of quarks and gluons inside nucleons
  - The spin structure of protons and neutrons
  - Glue in the proton's spin
  - The role of strange quarks
  - The hadron spectrum
  - The emergence of nuclei from QCD

View from the NSAC Performance Measures

Lattice calculations of hadron structure address 12 of 13 Updated 2008 Performance Measures

Year	#	Milestone
2009	HP3	Complete the combined analysis of available data on single π, η, and K photo-production of nucleon resonances and incorporate the analysis of two-pion final states into the coupled-channel analysis of resonances.
2010	HP4	Determine the four electromagnetic form factors of the nucleons to a momentum-transfer squared, Q^2, of 3.5 GeV^2 and separate the electroweak form factors into contributions from the u, d and s-quarks for $Q^2 < 1$ GeV^2 .
2010	HP5	Characterize high-momentum components induced by correlations in the few-body nuclear wave functions via (e,e'N) and (e,e'NN) knock-out processes in nuclei and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e},e\vec{p})$ reaction.
2011	HP6	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$ for x=0.2-0.6, and $1 < Q^2 < 5$ GeV^2 for both protons and neutrons.
2012	HP7	Measure the electromagnetic excitations of low-lying baryon states (<2 GeV) and their transition form factors over the range $Q^2 = 0.1$ – 7 GeV^2 and measure the electro- and photo-production of final states with one and two pseudoscalar mesons.

2012	HP11 (update of HP2)	Measure the helicity-dependent and target-polarization-dependent cross-section differences for Deeply Virtual Compton Scattering (DVCS) off the proton and the neutron in order to extract accurate information on generalized parton distributions for parton momentum fractions, x, of 0.1 – 0.4, and squared momentum transfer, t, less than 0.5 GeV^2.
2013	HP8	Measure flavor-identified q and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of W production.
2013	HP12 (update of HP1)	Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton.
2014	HP9	Perform lattice calculations in full QCD of nucleon form factors, low moments of nucleon structure functions and low moments of generalized parton distributions including flavor and spin dependence.
2014	HP10	Carry out ab initio microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origin of the nucleon-nucleon interaction.
2015	HP13 (new)	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering
2018	HP14 (new)	Extract accurate information on spin-dependent and spin-averaged valence quark distributions to momentum fractions x above 60% of the full nucleon momentum
2018	HP15 (new)	The first results on the search for exotic mesons using photon beams will be completed.

Spires 2008 TopCites in hep-lat

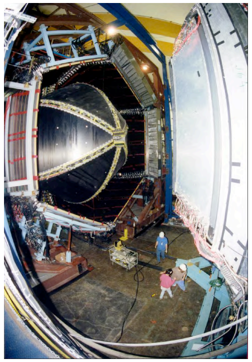
One USQCD 2008 article in hadon structure, spectroscopy and interactions included in hep-lat TopCites

Nucleon Generalized Parton Distributions from Full Lattice QCD
By LHPC Collaborations (Ph. Hagler et al.).
Published in:Phys.Rev.D77:094502,2008 (arXiv:0705.4295 [hep-lat])
[64 Total citations in HEP]

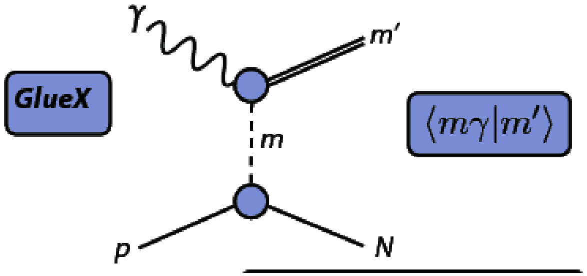
Hadron Spectroscopy

- **Spectroscopy is a classic tool for gleaning information about structure of theory**

- **Both experimental and *ab initio* N* and Exotic-meson programs aim at *discovering effective degrees of freedom of QCD*, and resolving competing low-energy models**
  - **Hadron Physics 2009 and 2012 milestones**
  - **Excited Baryon Analysis Center (EBAC) at Jefferson Lab**

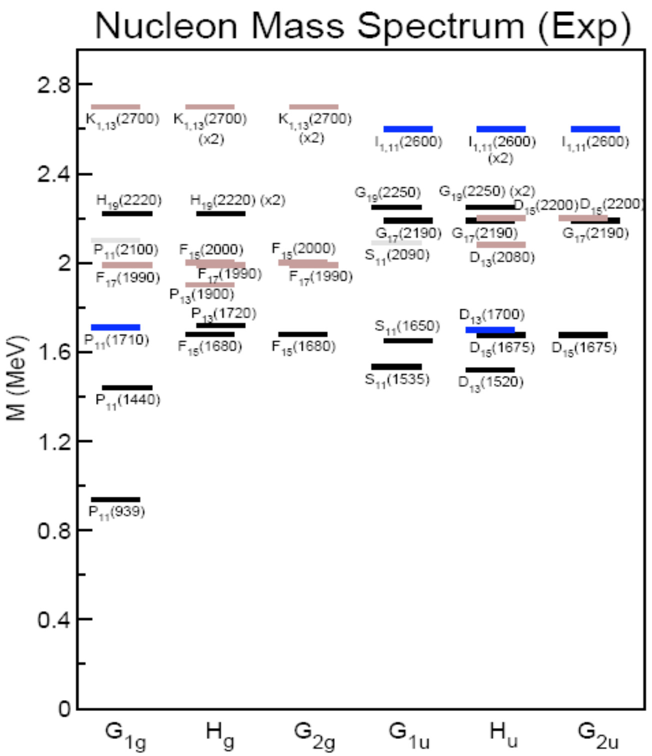


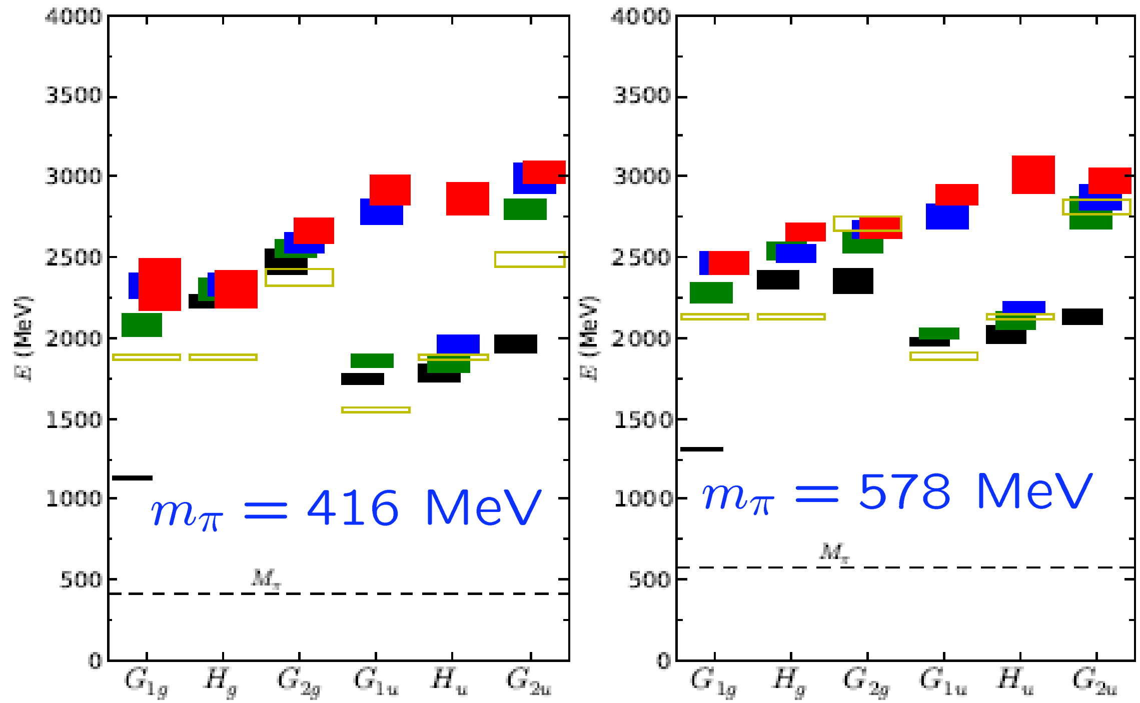
- **Spectroscopy of Exotic Mesons is a flagship component of CEBAF@12GeV**



Lattice QCD and Baryon Spectrum

Hadron Spectrum Collab., Phys.Rev.D79:034505 (2009)





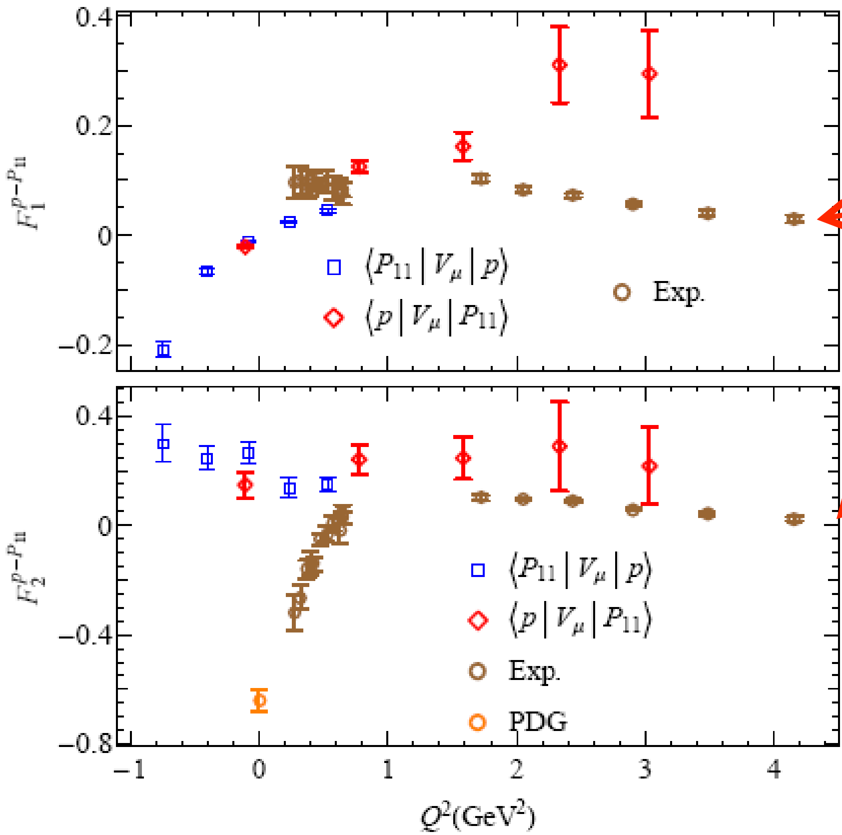
Lattices generated at ORNL under INCITE
Analyzed using USQCD resources

- ***Emergence of pattern seen in experiment!***
- ***First identification of spin-5/2 state in LQCD***

Nucleon-Roper Transition

- First measurement of nucleon-Roper transition form factor
- *Quenched calculation, at high pion mass*
- Measurements by CLAS at JLab

H-W Lin et al., Phys.Rev.D78:114508 (2008).



CLAS

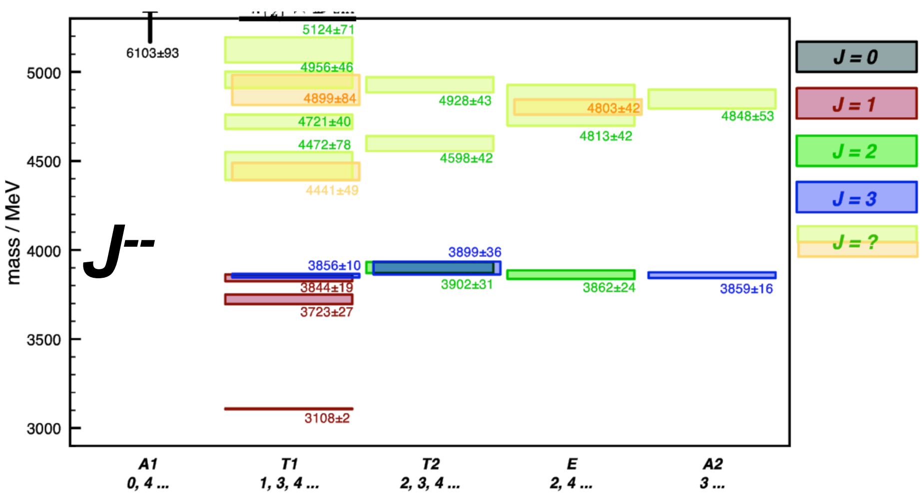
Charmonium Spectroscopy

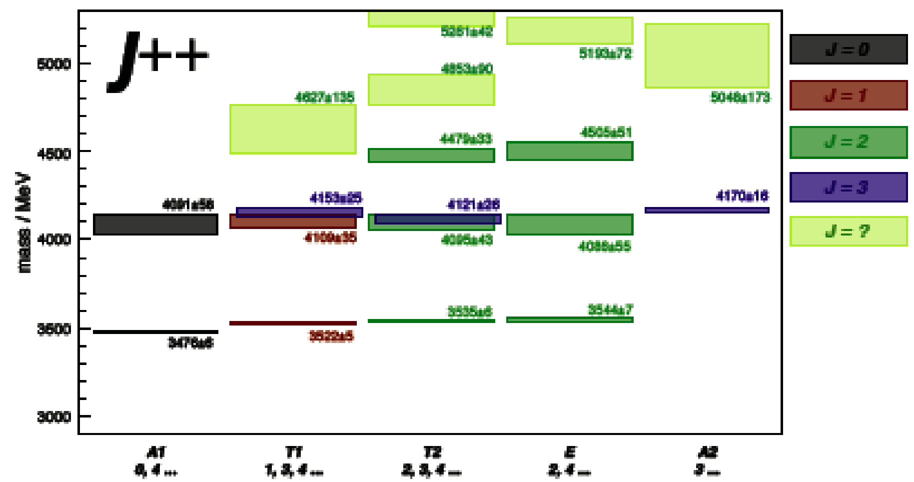
using a large basis of operators extracted a meson spectrum including excited states and exotic J^{PC}

"Charmonium excited state spectrum in lattice QCD"
(JJD, RGE, DGR, Nilmani Mathur) *Phys.Rev.D77:034501,2008*

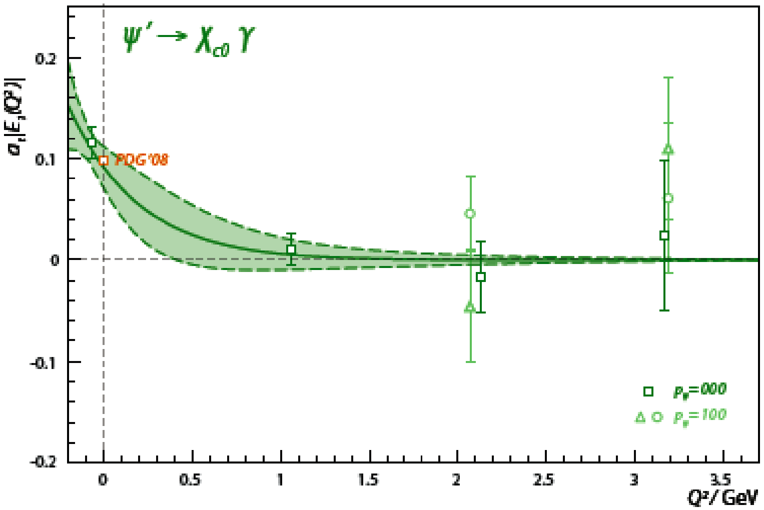
built bound-state model interpretation of spectrum and matrix elements - identified hybrid-like states with non-exotic J^{PC}

"Charmonium in lattice QCD and the non-relativistic quark-model"
(JJD, Ermal Rrapaj) *Phys.Rev.D78:094504,2008*



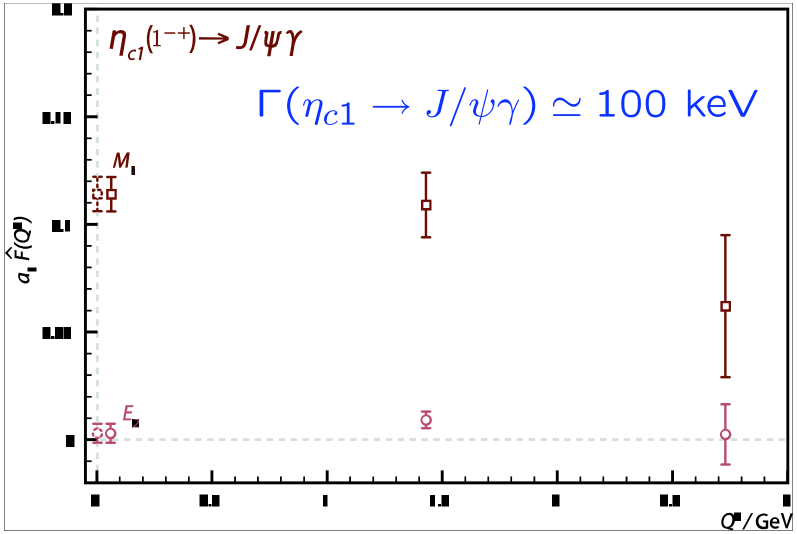


Preparing for GlueX: Radiative Transitions



J Dudek, R Edwards, C Thomas, arXiv:0902.2241, PRD in press

Use of variational method, and the optimizied meson operators, to compute radiative transitions between excited states and exotics.

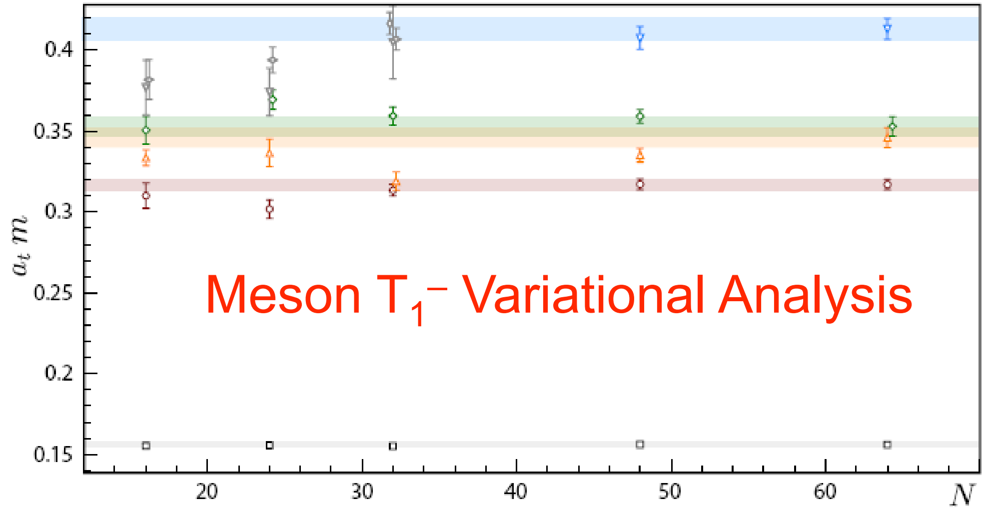


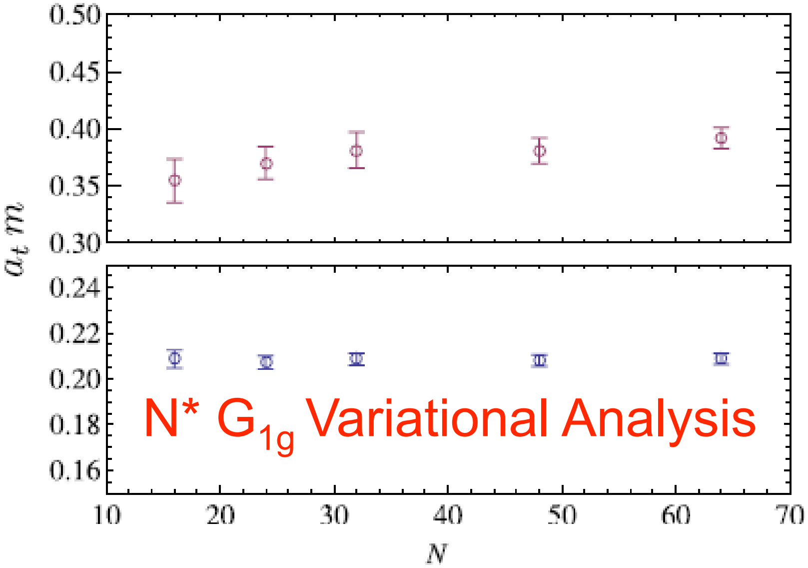
considerable phenomenology developed from the results - supports non-relativistic models and limits possibilities for form of excited glue

Radiative width of hybrid comparable to conventional meson – important for GlueX

New method for correlation functions

- Major challenge: efficient calculation of hadron correlation functions, including those for multi-hadron states
- New method – distillation – introduced by *Peardon et al., arXiv: 0905.2160*
- Expand smearing function in truncated eigenvector basis





Errors < 3% on low-lying energies

Spectroscopy – Opportunities

- **Accomplishments**
  - Development of methodology to extract the resonance spectrum for states containing quarks
  - Demonstration of ability to extract many energy levels in N* and hybrid resonance spectrum: first identification of spin-5/2 state
  - Transition form factor to Roper resonance in quenched QCD
  - Pioneering calculations of photo-transition amplitudes in charmonium, important for CLEO-c, and of 2γ width
  - Tuning of anisotropic clover action, and new method for setting scale and quark masses
  - Development of new methodology for efficient evaluation of hadron correlation functions
- **Goals**
  - Low-lying baryon spectrum for states composed of u/d and s quarks, with scattering states delineated
  - Low-lying exotic meson spectrum; first calculation of photo-couplings involving conventional and exotic mesons

Spectroscopy - Opportunities

L_s(fm)	2.45fm	2.95fm	3.93fm	4.91fm
m_π(MeV)	$20^3 \times 128$	$24^3 \times 128$	$32^3 \times 256$	$40^3 \times 256$
833	6k, TACC[1.0M](10)			
560	7k, TACC[1.5M](6.7)			
448	8k, TACC[2.1M](5.4)			
383	13k, done	13k, done	11k, Tenn[22M](7.4)	
230		6k, PSC[6M](3.2)	11k, ORNL[70M](4.2)	
140				11k, INCITE[390M](3.4)

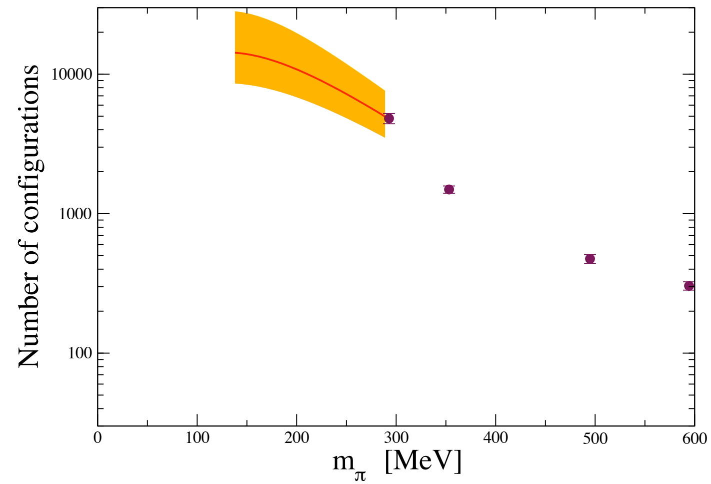
Hadron Structure

- Nucleon observables central to nuclear physics
  - Form factors - distribution of charge and magnetization, onset of scaling
  - Moments of structure functions - distribution of quarks and gluons
  - Moments of generalized parton distributions
    - Orbital angular momentum carried by quarks
    - Transverse structure of nucleon
    - Complementary to expt. measurement of GPD’s
- Calculations with N_f =2+1 dynamical quarks
  - Mixed action - Domain wall valence quarks on improved staggered sea - provided first entree to chiral regime
  - Dynamical domain wall now providing precision results

Crucial issues for nucleon structure

- Signal to noise degrades as pion mass decreases
  Use 3000 - 7000 measurements

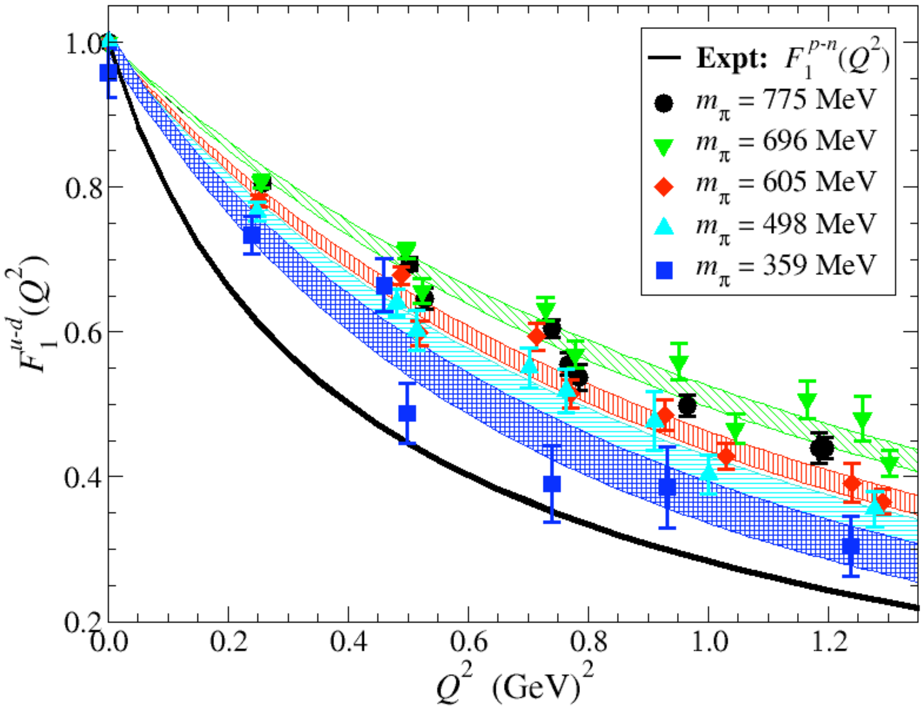
$$\frac{\text{Signal}}{\text{Noise}} = \frac{\langle J(t)J(0)\rangle}{\frac{1}{\sqrt{N}}\sqrt{\langle |J(t)J(0)|^2\rangle - (\langle J(t)J(0)\rangle)^2}}$$
$$\sim \frac{Ae^{-M_N t}}{\frac{1}{\sqrt{N}}\sqrt{Be^{-3m_\pi t} - Ce^{-2M_N t}}}$$
$$\sim \sqrt{N}De^{-(M_N - \frac{3}{2}m_\pi)}$$

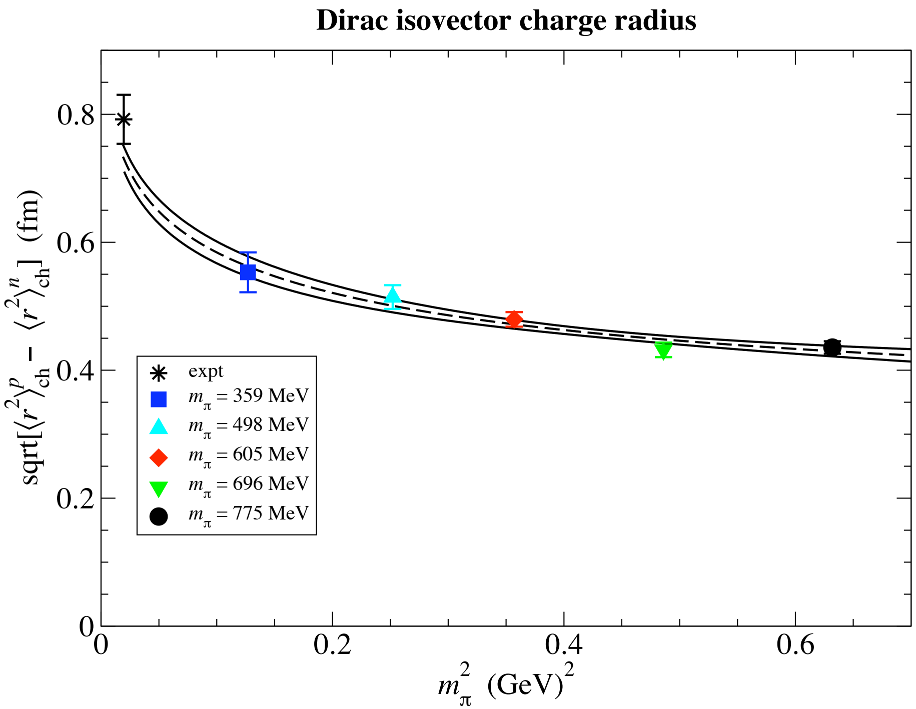


- Chiral extrapolation $\sim m_\pi^2 ln(m_\pi^2),\ ln(m_\pi^2)$
  - Many variants, uncertain range of validity

Electromagnetic Form Factors

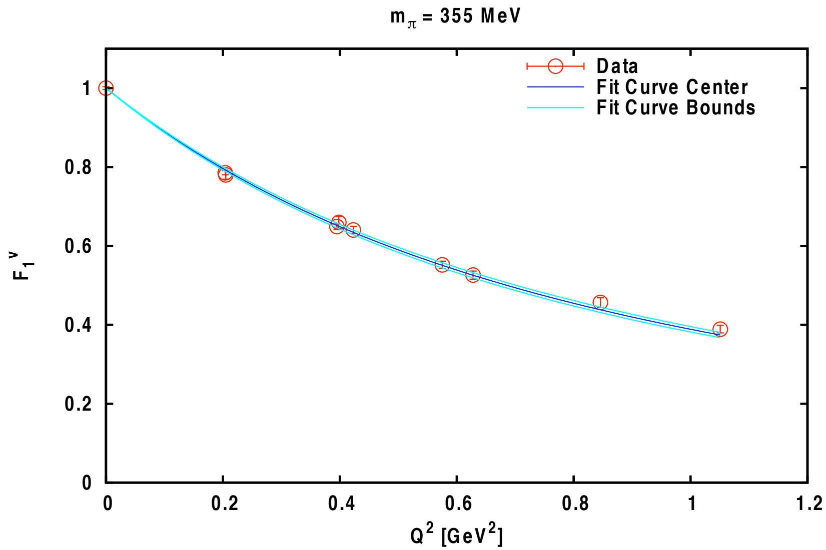
LHPC, hep-lat/0610007   mixed action

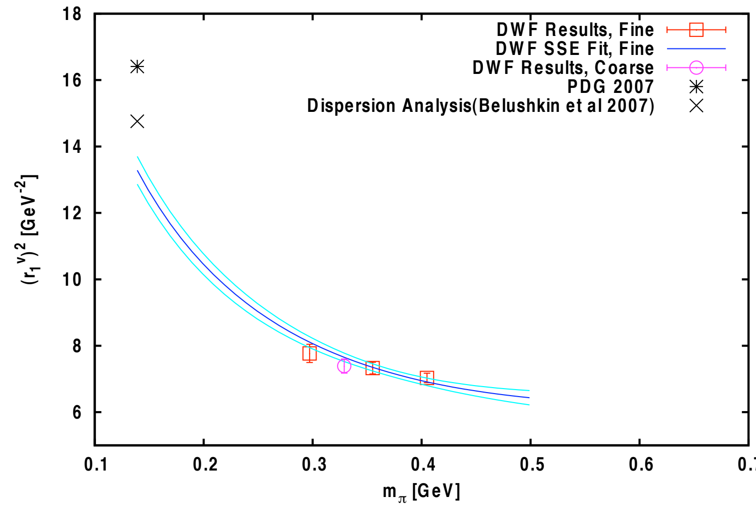


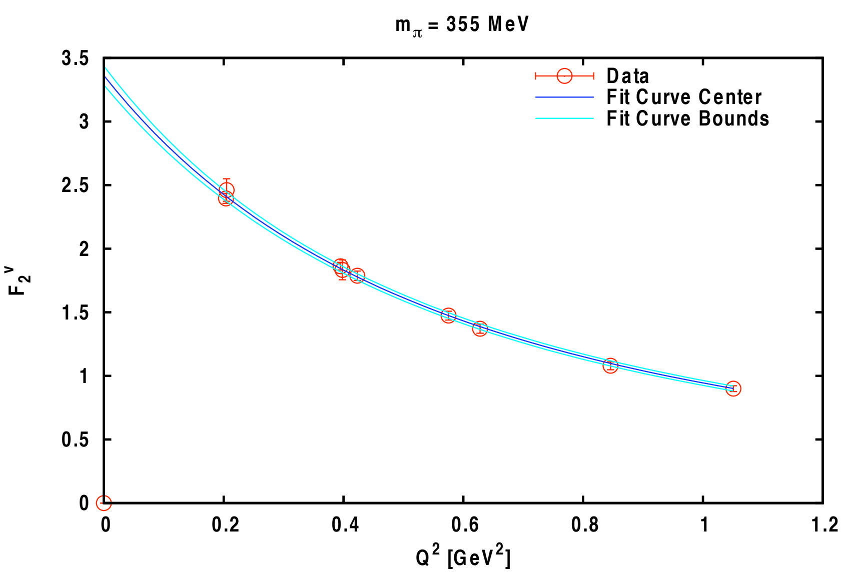


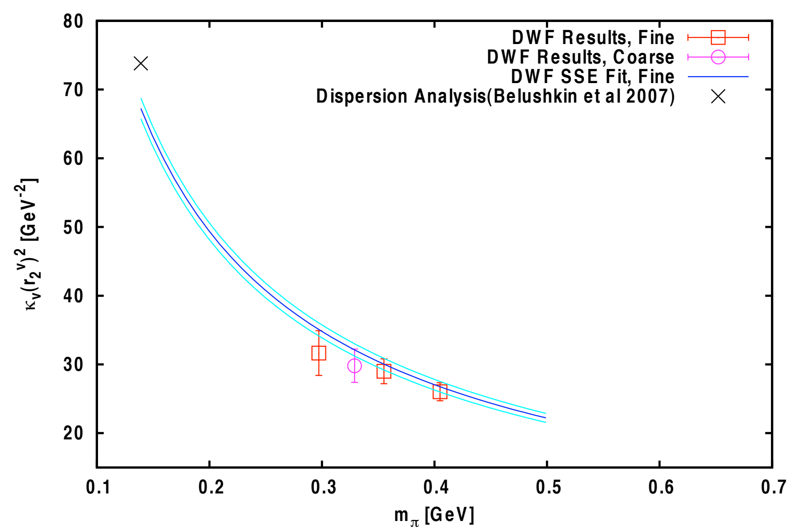
$$\langle r^2\rangle^{u-d} = a_0 - \frac{(1+5g_A^2)}{(4\pi f_\pi)^2}\log\left(\frac{m_\pi^2}{m_\pi^2+\Lambda^2}\right)$$

High Precision Form Factors

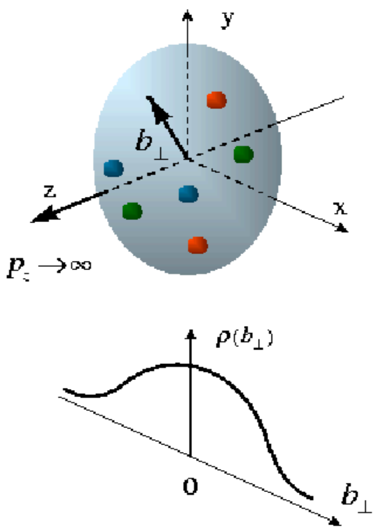


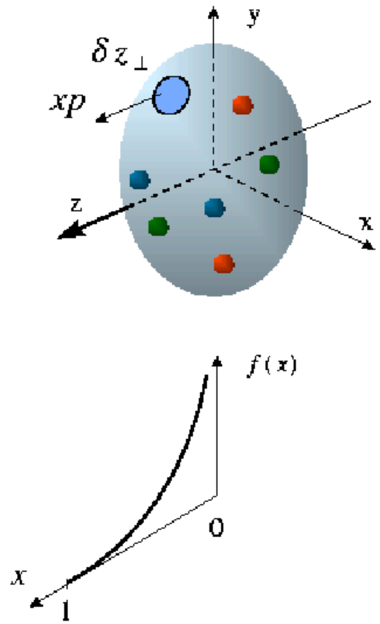


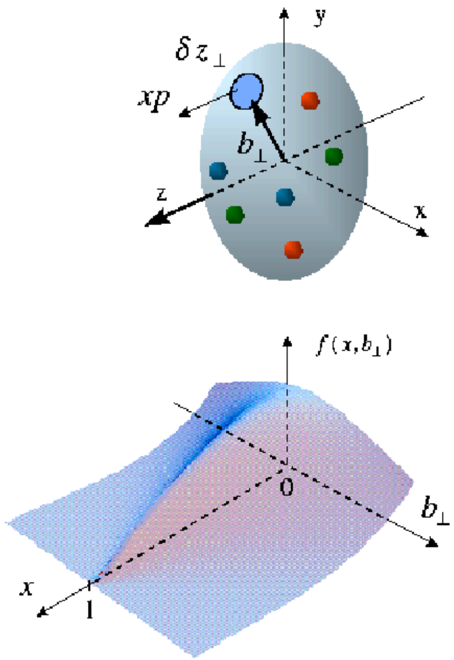




GPDs: Different Regimes in Different Experiments







Form Factors

transverse quark distribution in Coordinate space

Structure Functions

longitudinal quark distribution in momentum space

GPDs

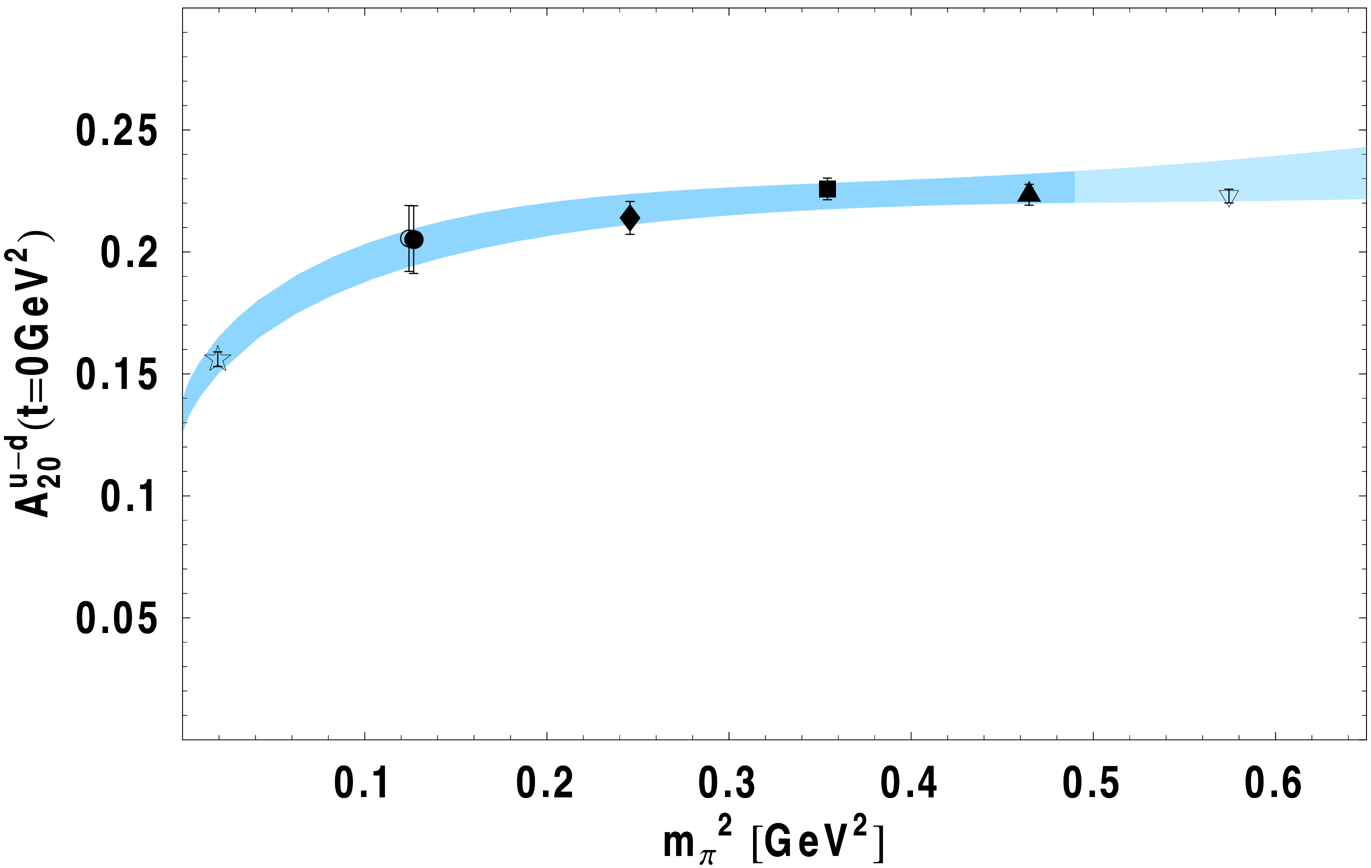
full quark distribution in both coordinate and momentum space

Chiral extrapolation $\langle x \rangle_q^{u-d} = A_{20}^{u-d}(t=0)$

Global fit to A, B, C with 9 fit parameters

$$A_{20}^{u-d}(t, m_\pi) = A_{20}^{0,u-d}\left(f_A(m_\pi) + \frac{g_A^2}{192\pi^2 f_\pi^2} h_A(t, m_\pi)\right) + \widetilde{A}_{20}^{0,u-d} j_A(m_\pi) + A_{20}^{m_\pi, u-d} m_\pi^2 + A_{20}^t t$$
$$\sim a\left(1 - \frac{3g_A^2+1}{4\pi f_\pi^2} m_\pi^2 \ln m_\pi^2\right) + b m_\pi^2 \cdots$$

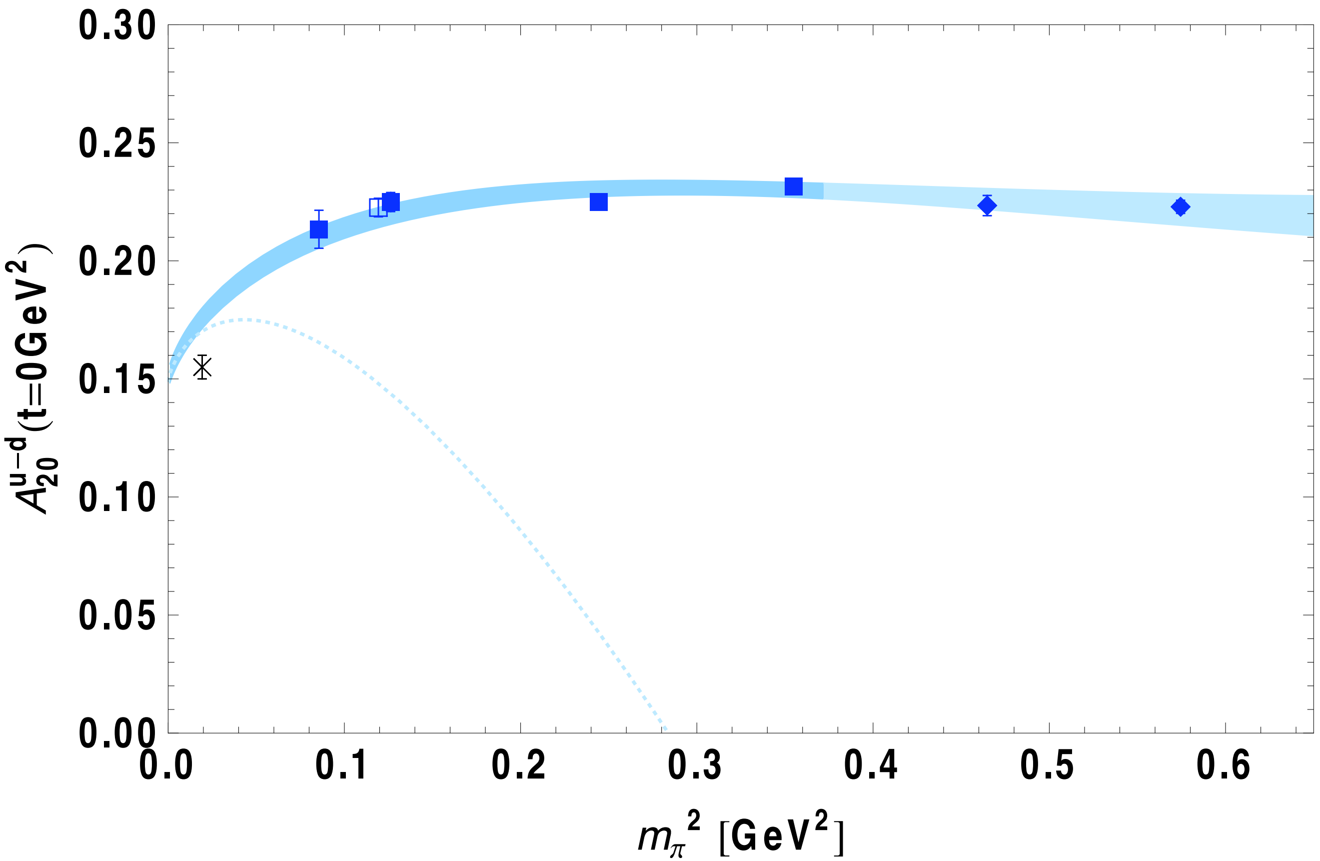
(LHPC Phys. Rev. D77, 094502 (2008))



Chiral extrapolation II $\langle x \rangle_q^{u-d} = A_{20}^{u-d}(t=0)$

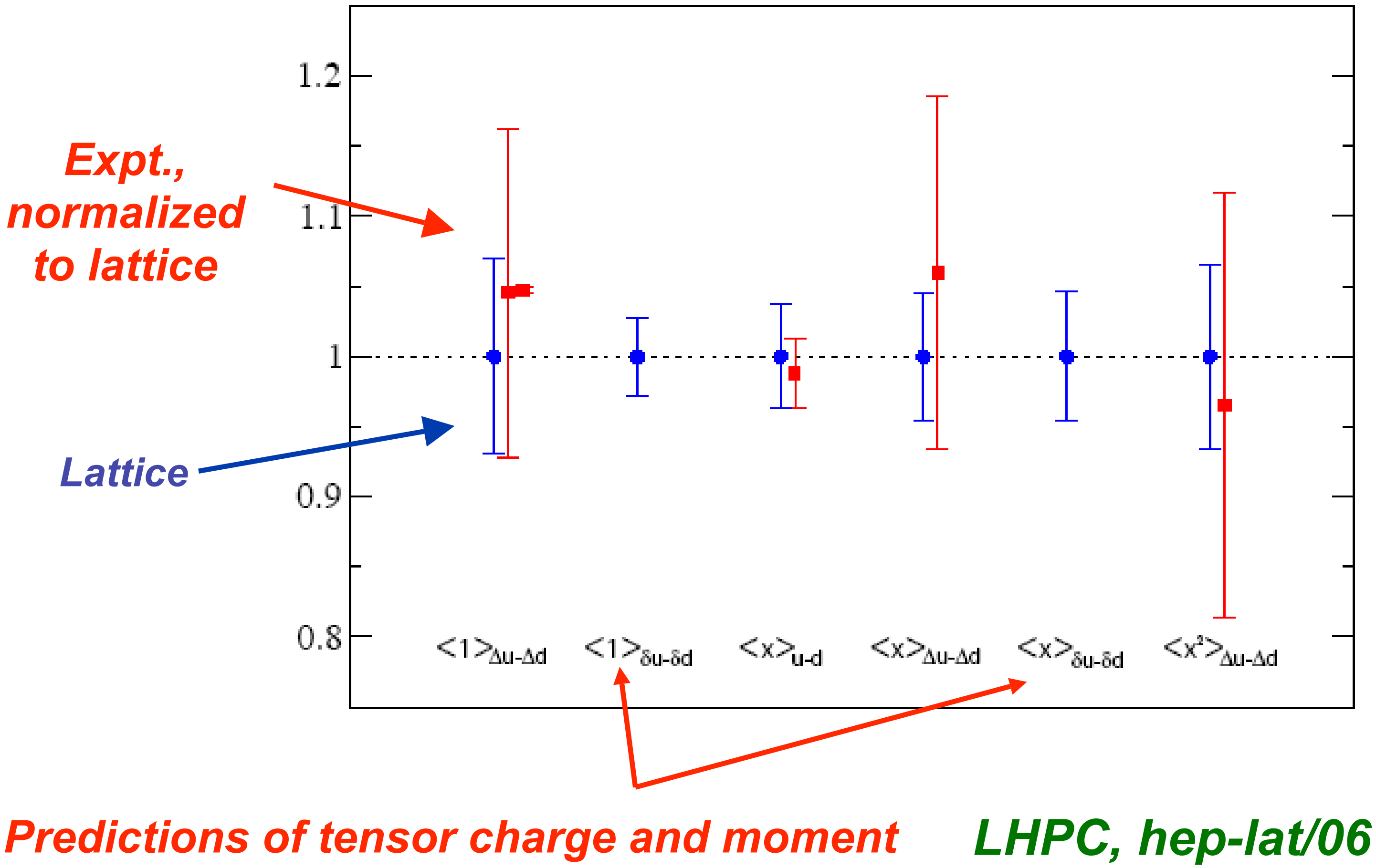
- High statistics calculation including lower mass fails to see expected chiral behavior
- Emerging theme in all high statistics calculation

(LHPC to be published)



Chiral Extrapolation - III

Crucial to calculate down to physical quark mass in large volumes to make credible predictions

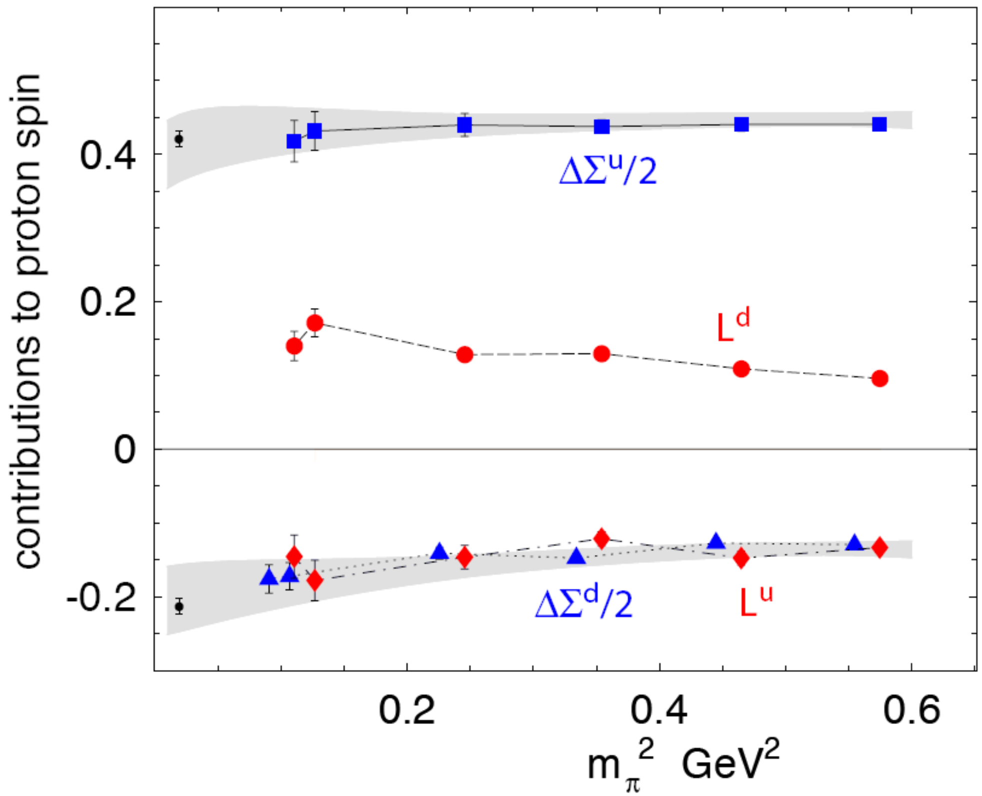


LHPC, hep-lat/0610007

Origin of the nucleon spin

Ji Sum Rule: $J_q = \frac{1}{2}[A_{20}^{u+d}(0) + B_{20}^{u+d}(0)] = \frac{1}{2}[\langle x \rangle_{u+d} + B_{20}^{u+d}(0)]$

$$\frac{1}{2}\Delta\Sigma = \frac{1}{2}\langle 1 \rangle_{\Delta u + \Delta d}$$



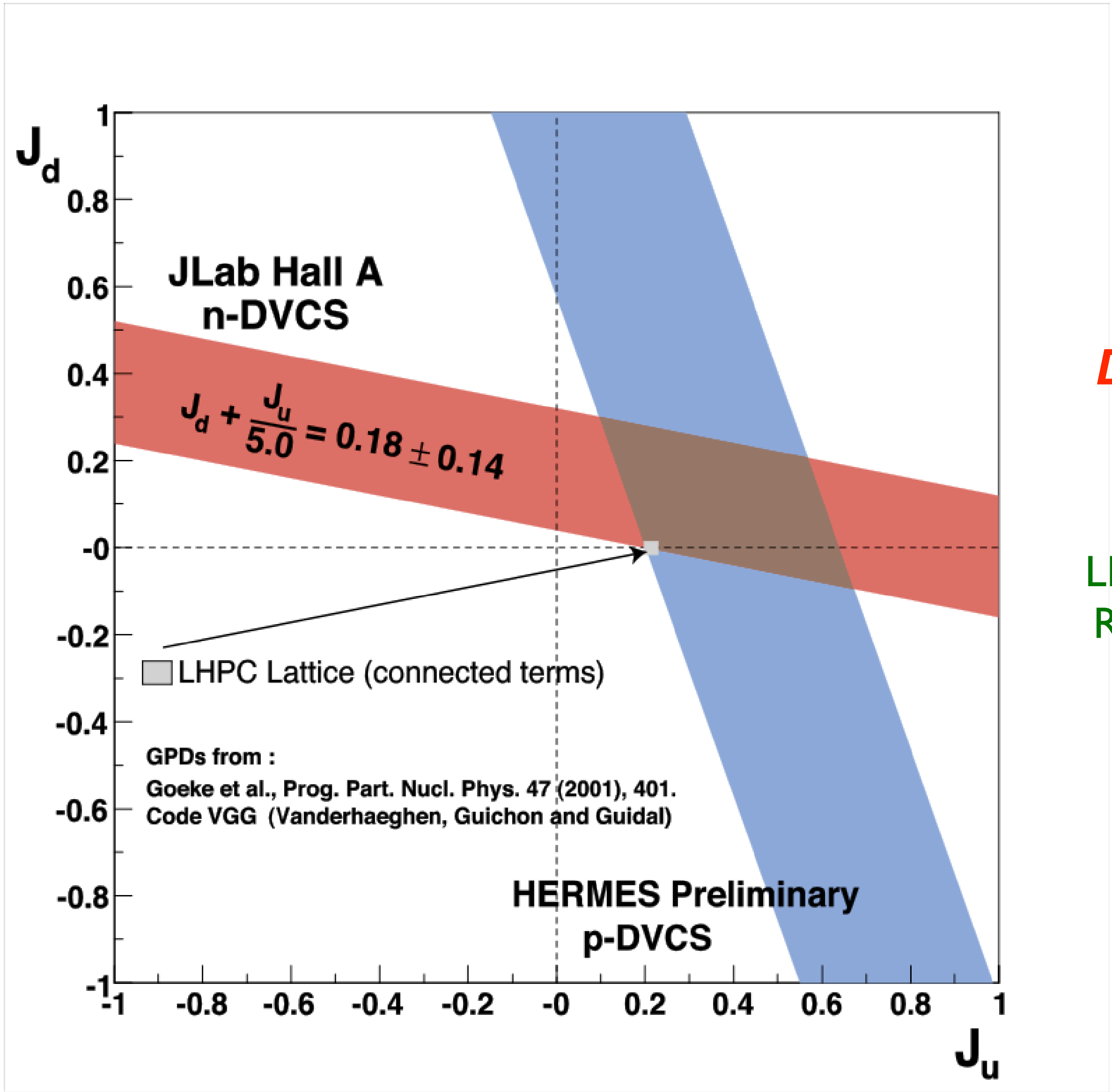
Surprises:

Total L negligible

Spin and L opposite

LHPC Phys Rev D77, 094502 (2008)

Origin of the nucleon spin



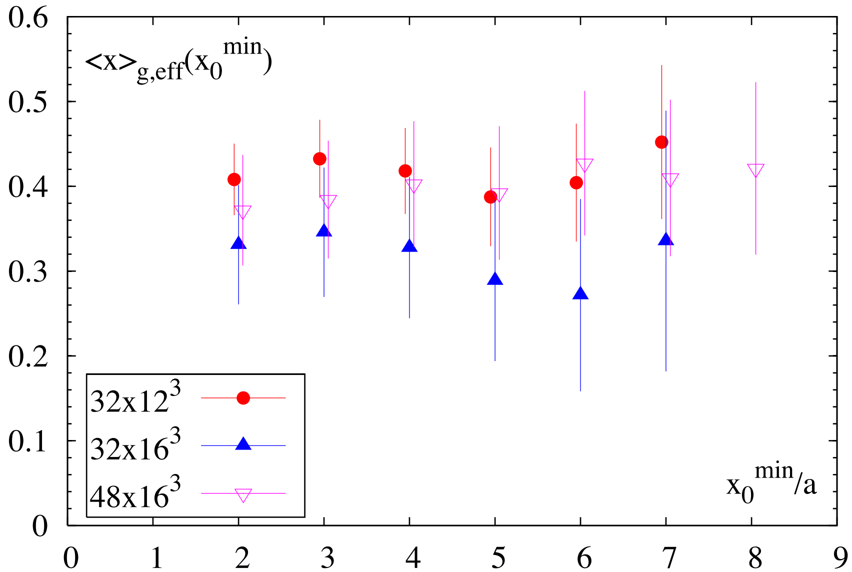
Lattice QCD + expt.

Discovering origin of nucleon spin

LHPC, Haegler et al., Phys. Rev. D 77, 094502 (2008)

Gluon momentum fraction in pion

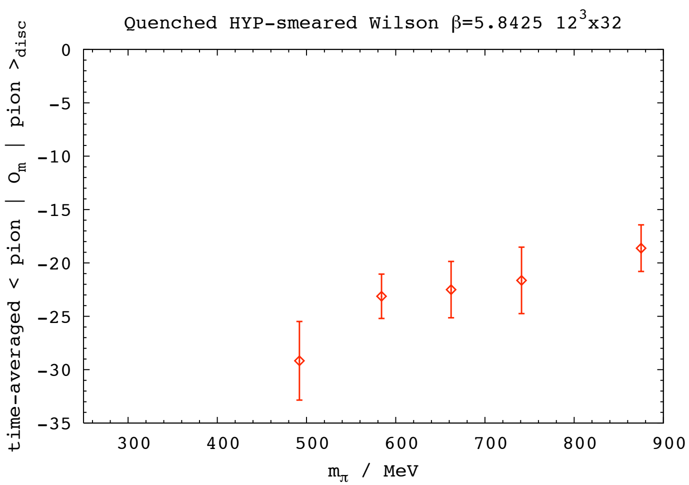
- Notoriously difficult: 5000 configurations - no signal
- Improved operator $E^2 - B^2$ (Signal improved x 40)
- Normalize operator by ratio of entropy at finite T
- $\langle x \rangle_{glue}$ (μ = 2 GeV) = 0.37 ± 8 ± 12
- Check: $\langle x \rangle_{glue} + \langle x \rangle_{quarks}$ = 0.99 ± 8 ± 12

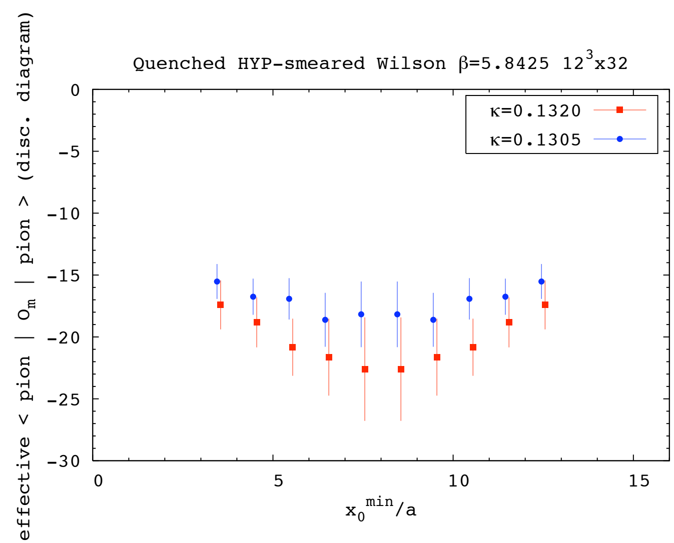


Harvey Meyer and J.N.
PRD 77 037501 (2008)

Disconnected Diagrams

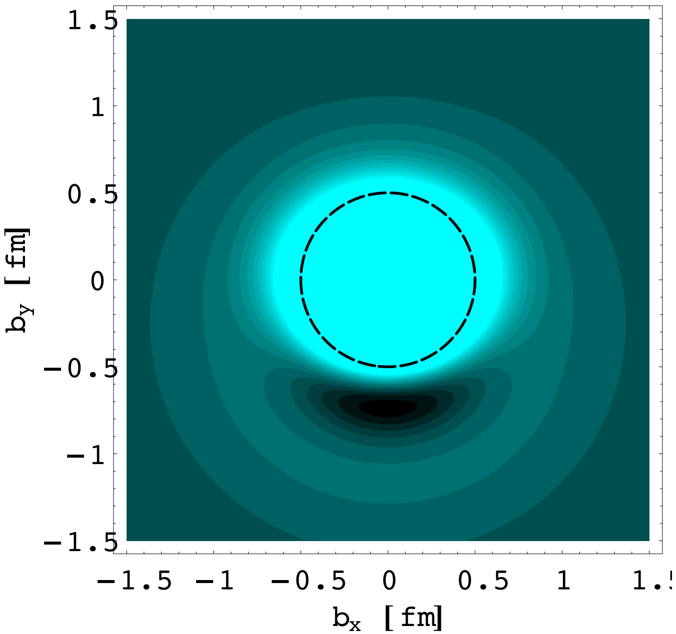
- Variance - start with dim 3 operators, coarse lattice
- Test case: $\bar{\psi}\psi$ in pion on quenched lattices
  - Calculate $\langle \eta^* (\chi - \chi_{hop}) \rangle_{n_1} + \langle \eta^* \chi_{hop} \rangle_{n_2}$
  - 492 MeV pion 26 inversions on 1000 lattices
    - connected 87(2) disconnected 29(4)



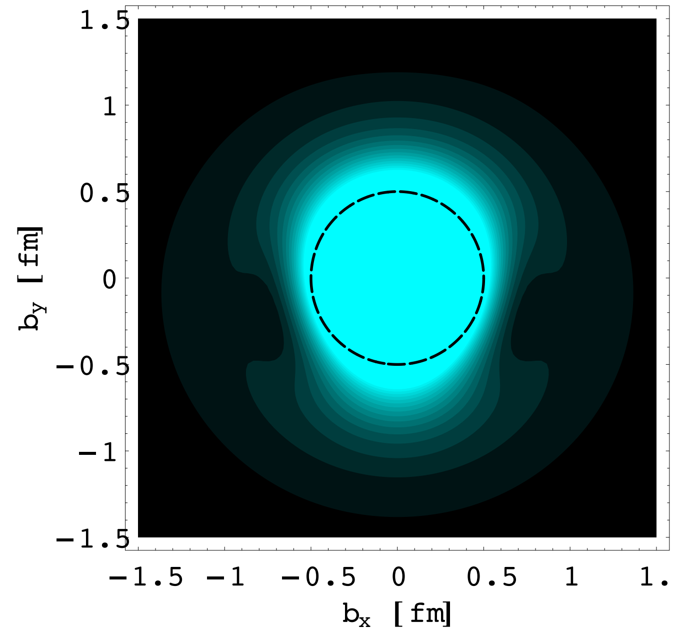


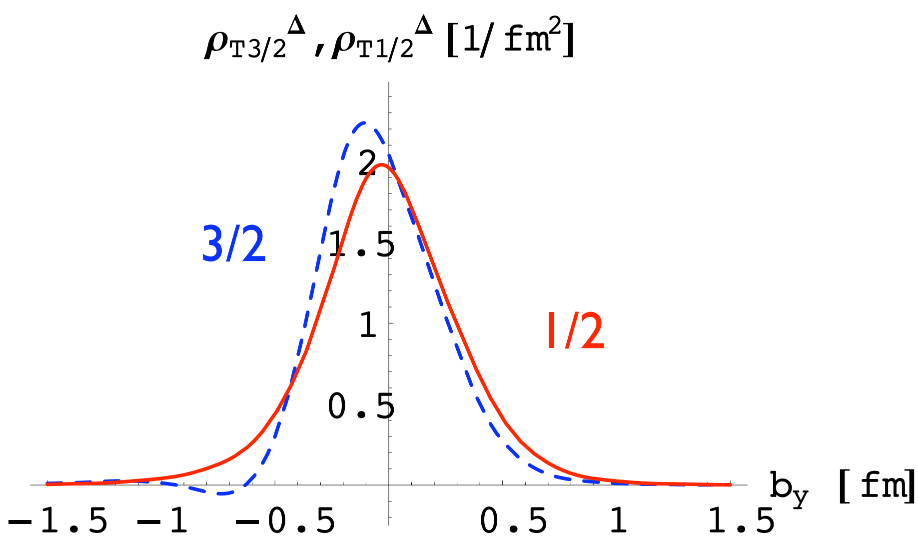
Quark transverse density in Delta

3/2



1/2





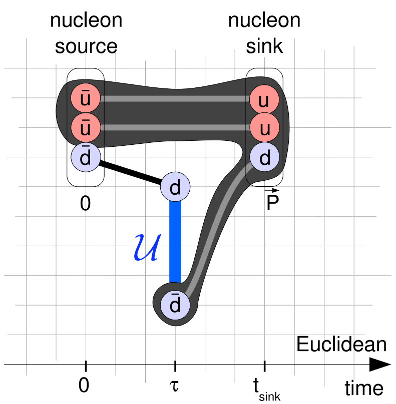
Spin in x direction

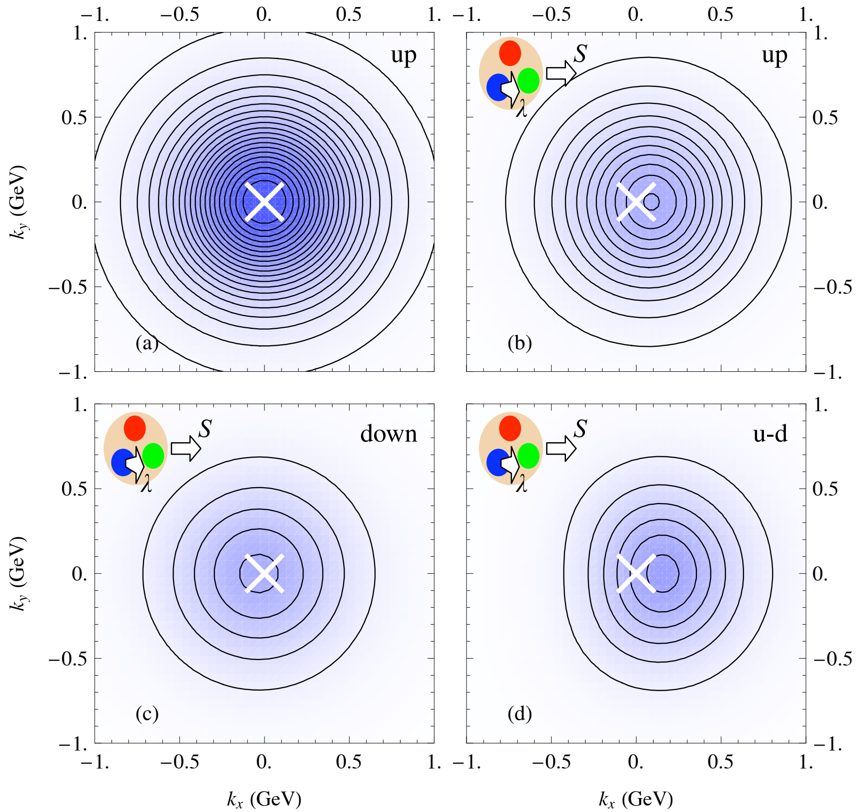
Construct from electric and magnetic form factors

Alexandrou. et al. arXiv:0901.3752

Transverse momentum-dependent quark distributions

Quark momentum distribution interesting and complementary to GPD's





B. Musch et. al.
arXiv 0811.15361

Hadron Structure- Opportunities

- Accomplishments
  - Hybrid action provided first entree to chiral regime
  - High precision DW calculations down to 300 MeV
  - Observables essential to experimental program
  - Insight - origin of spin, transverse structure of hadrons
- Challenges
  - Gluon observables
  - Disconnected diagrams
  - Calculate down to physical pion mass in large volume
    - Current puzzles with chiral behavior
    - Collaboration with RBC - roadmap: 2013 in small vol

Hadron-Hadron Interactions

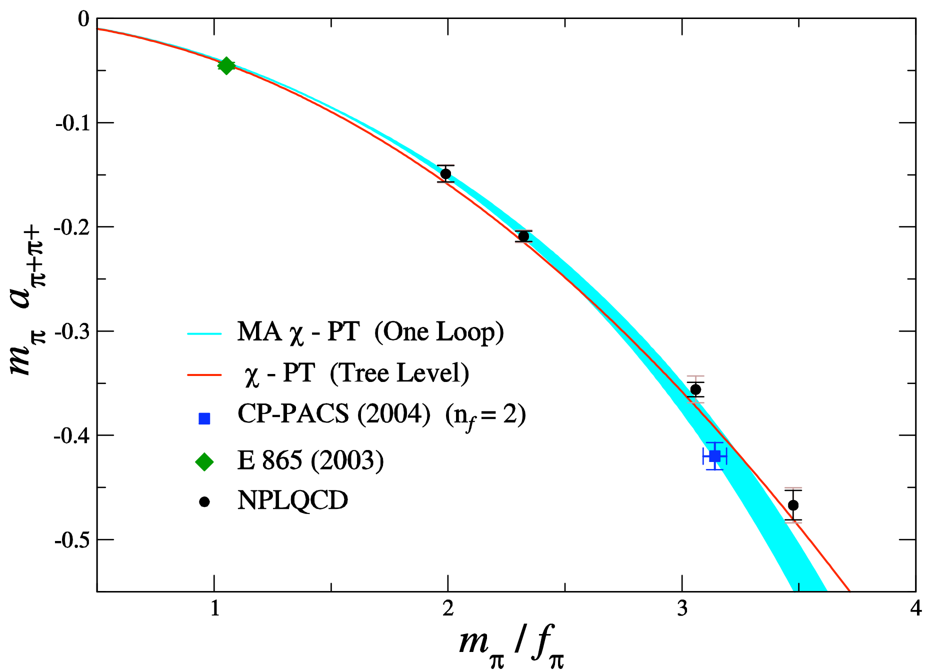
- **Grand Challenge to rigorously compute properties and interactions of nuclei**

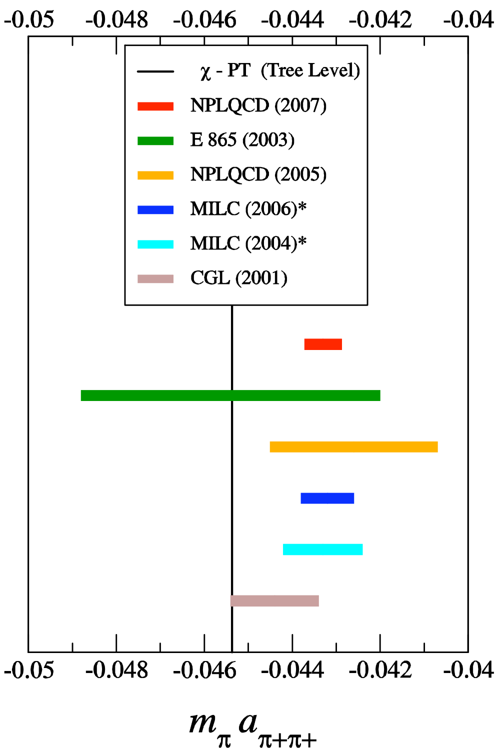
- **Hadron Physics 2014 milesone: *Ab intio microscopic calculations of light nuclei…. …based on two-nucleon, three-nucleon forces and lattice QCD…***

- **Hyperon-nucleon interaction, with dearth of experimental data, provide opportunity for lattice QCD to provide astrophysical insight: input to nuclear EOS in neutron stars**

Meson-Meson Interaction

- NPLQCD calculation using DWF valence quarks on N_f = 2 + 1 MILC configurations
- ChPT + lattice QCD at m_π down to 290 MeV

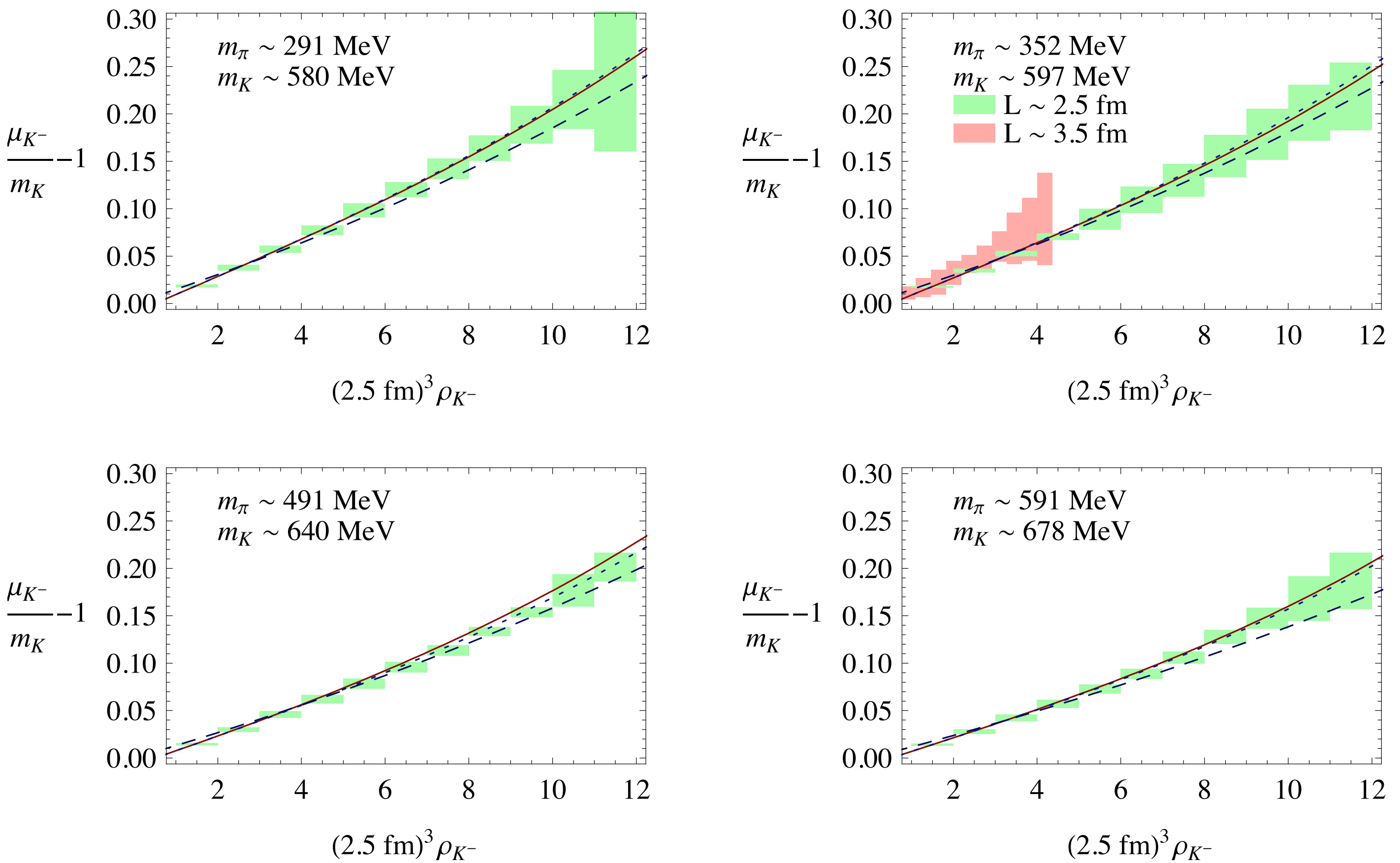




NPLQCD, arXiv:0706.3026

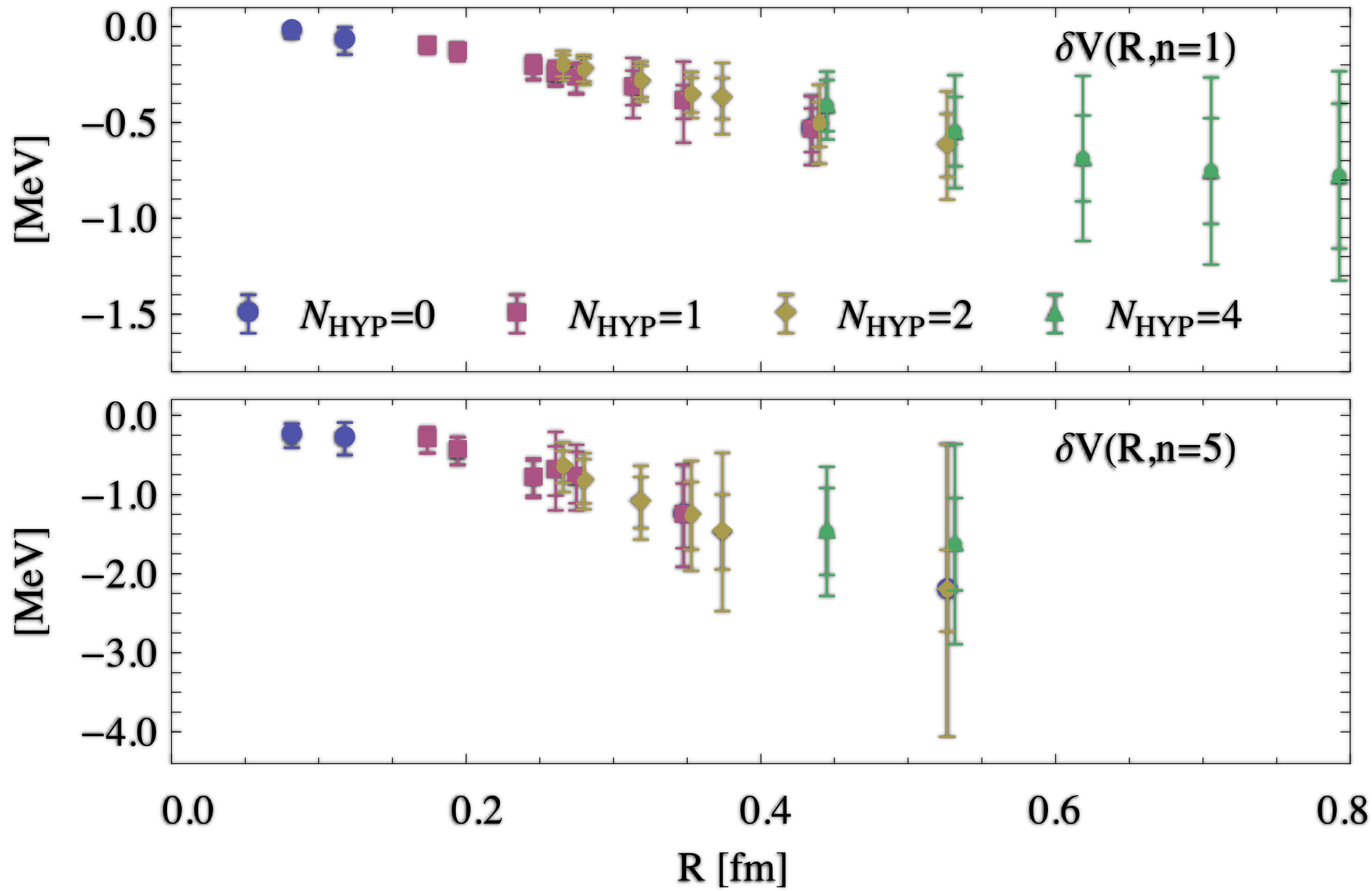
→ *High-precision computation*

Kaon Condensation



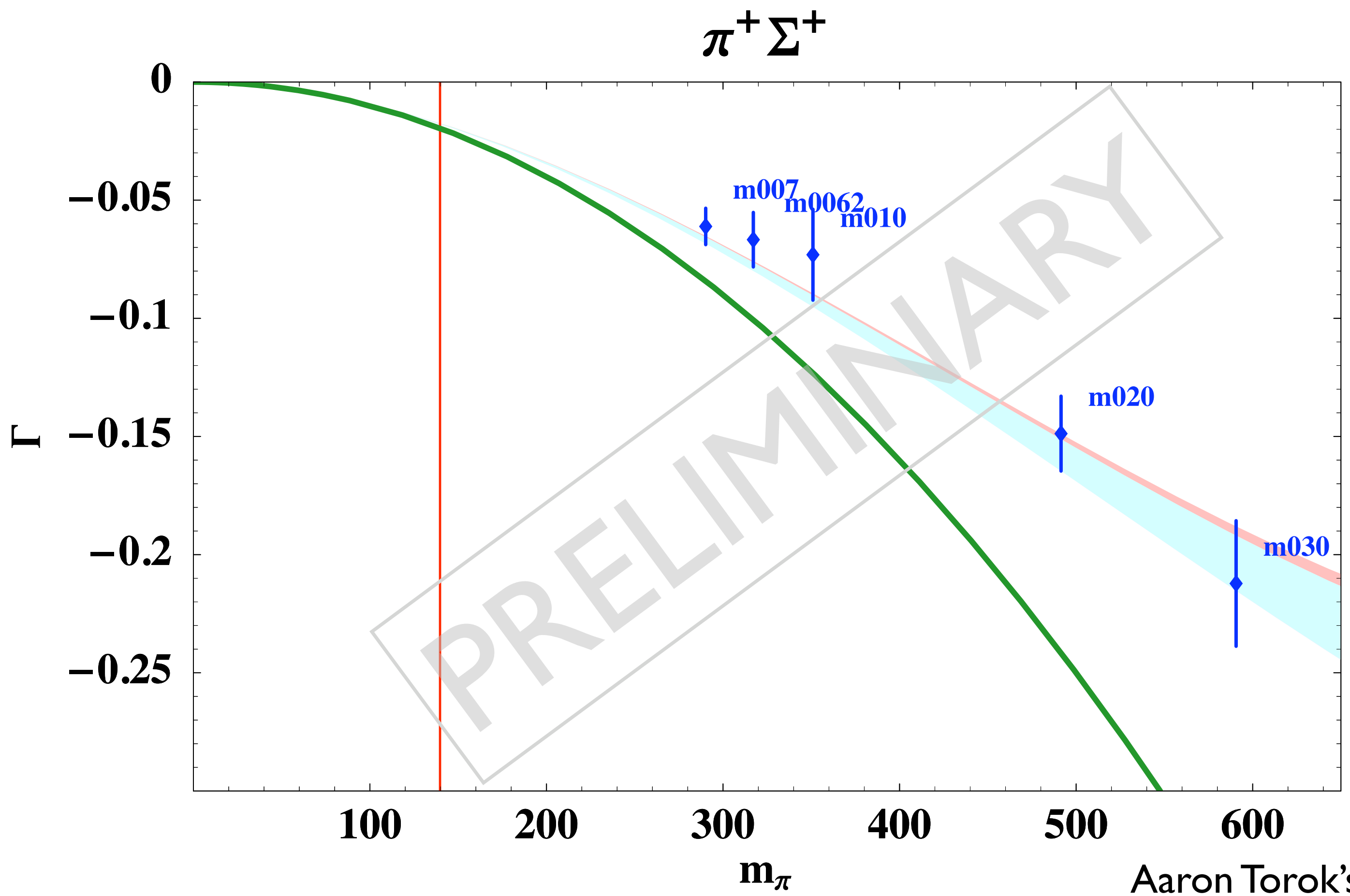
Publications : PRL 100,082004 (2008); PRD 77, 057502 (2008); PRD 78,014507 (2008); PRD 78,054514 (2008)

Color Screening



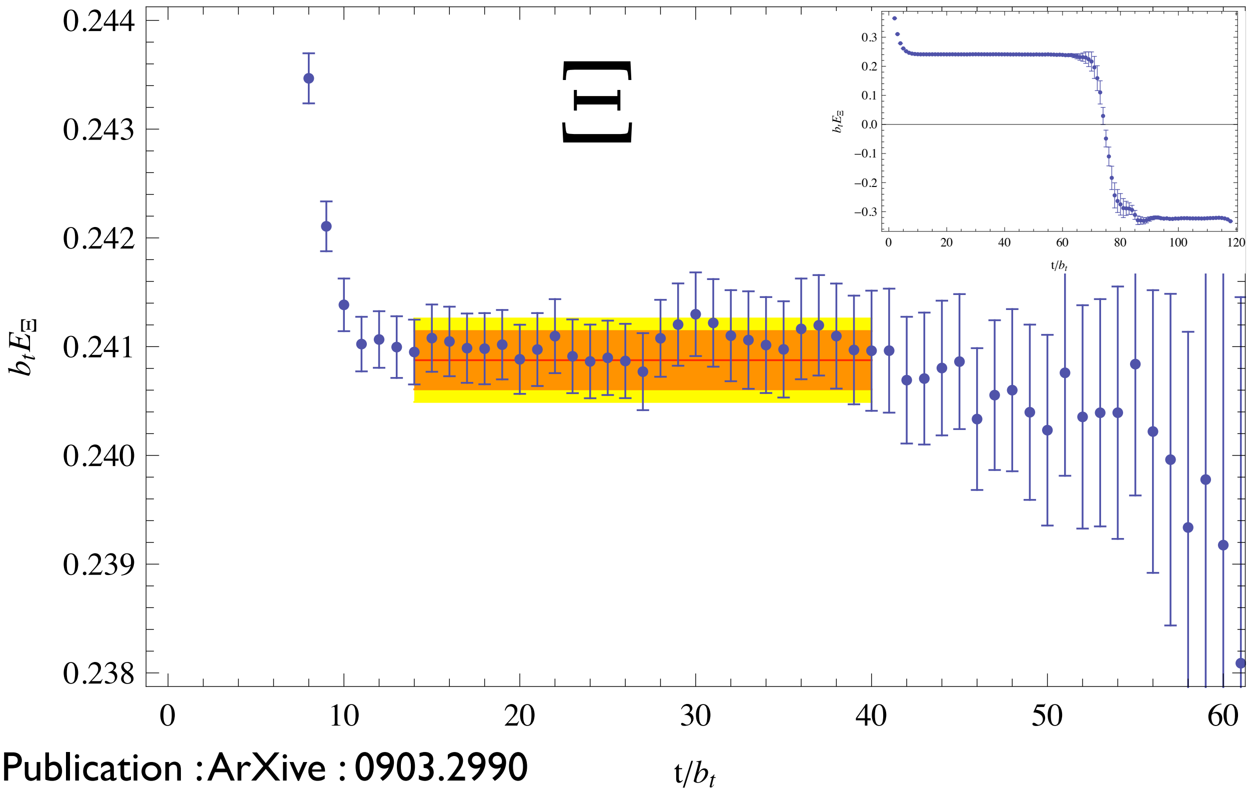
Publication : PRL 102,032004 (2009)

Meson-Baryon Scattering



Aaron Torok's PhD thesis
University of New Hampshire

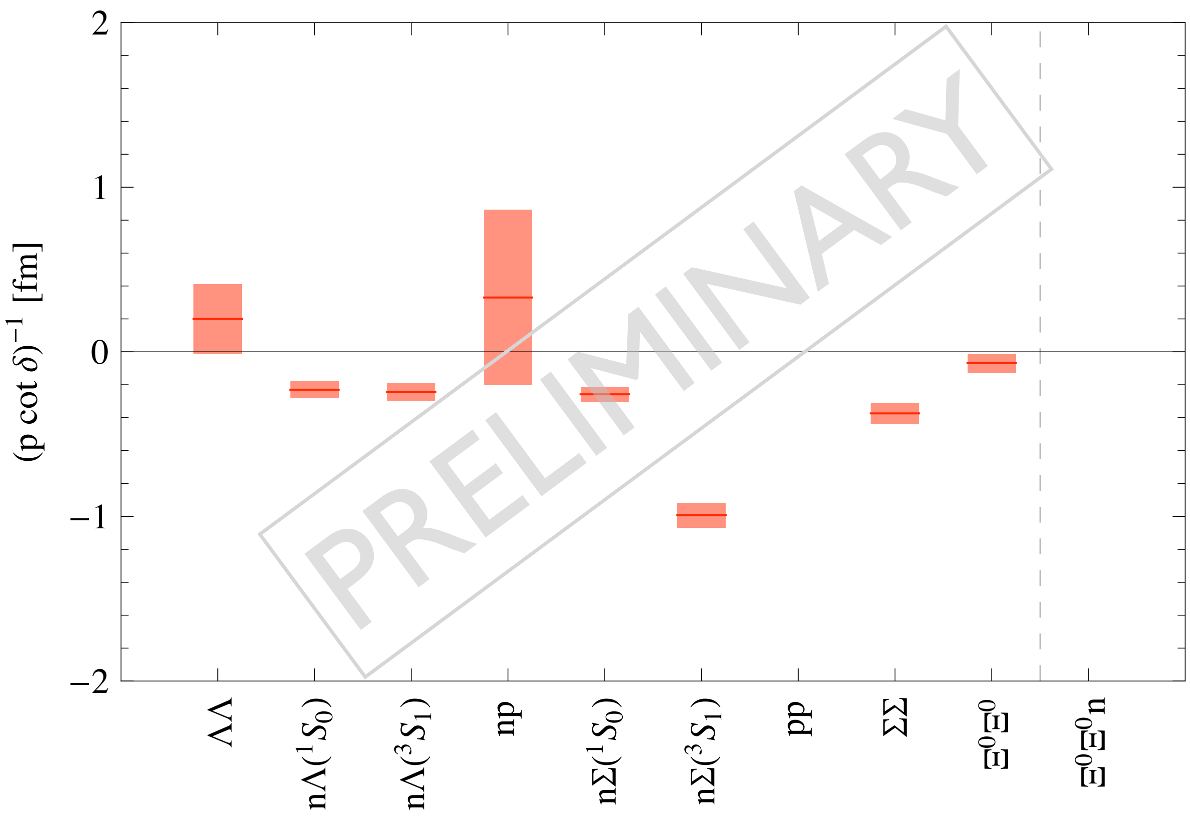
High Statistics Calculations on the Jefferson Lab Anisotropic Clover Lattices : Single Baryon Systems



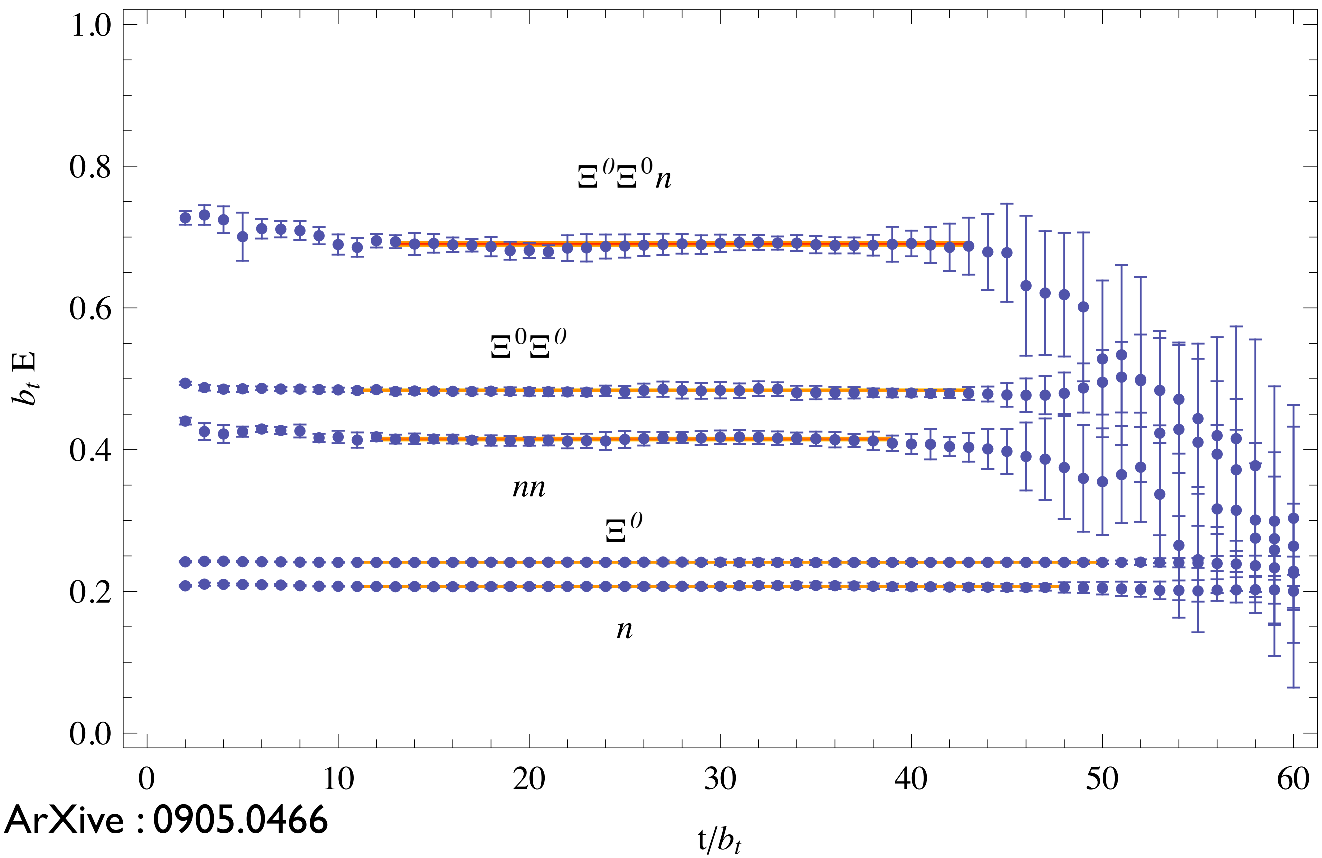
~0.2% Precision !

Publication : ArXive : 0903.2990

High Statistics Calculations on the Jefferson Lab Anisotropic Clover Lattices : Two Baryon Systems

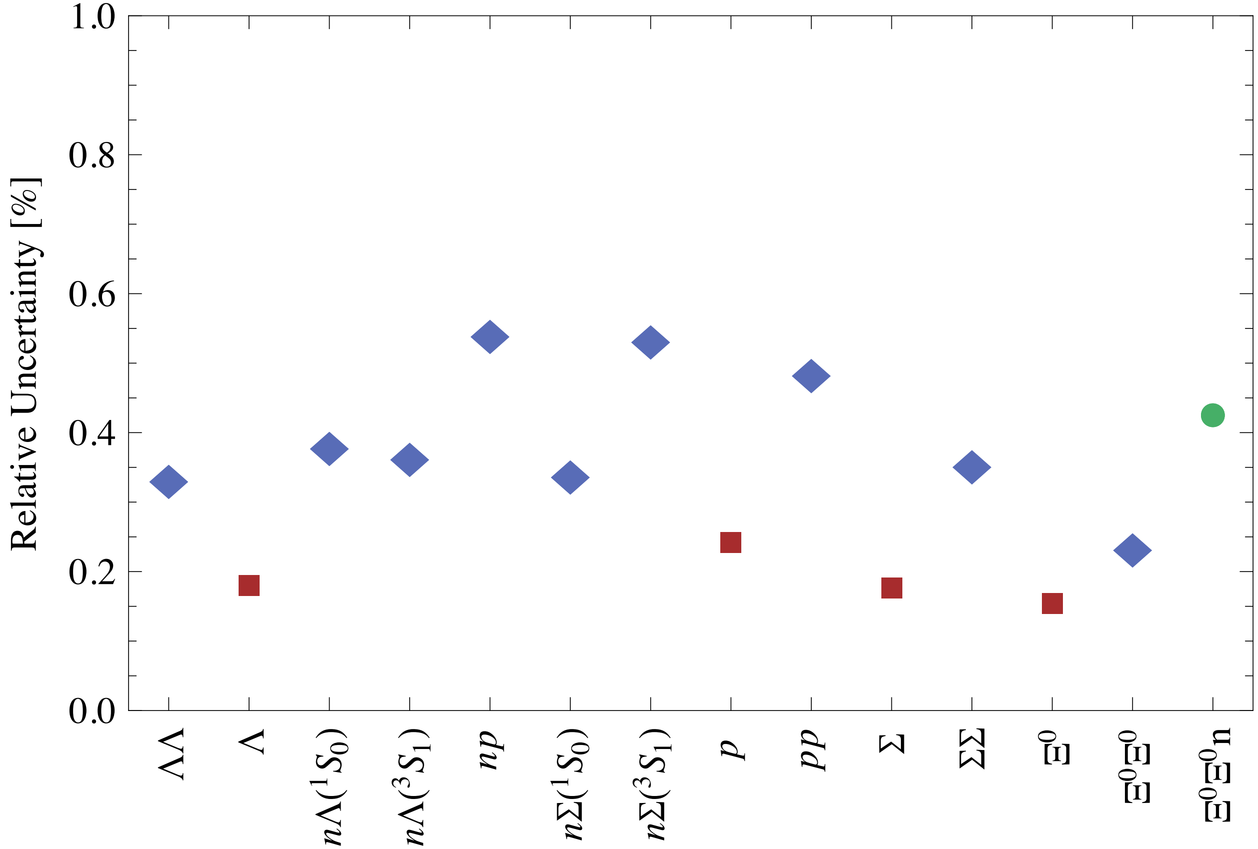


High Statistics Calculations on the Jefferson Lab Anisotropic Clover Lattices : Three Baryon Systems

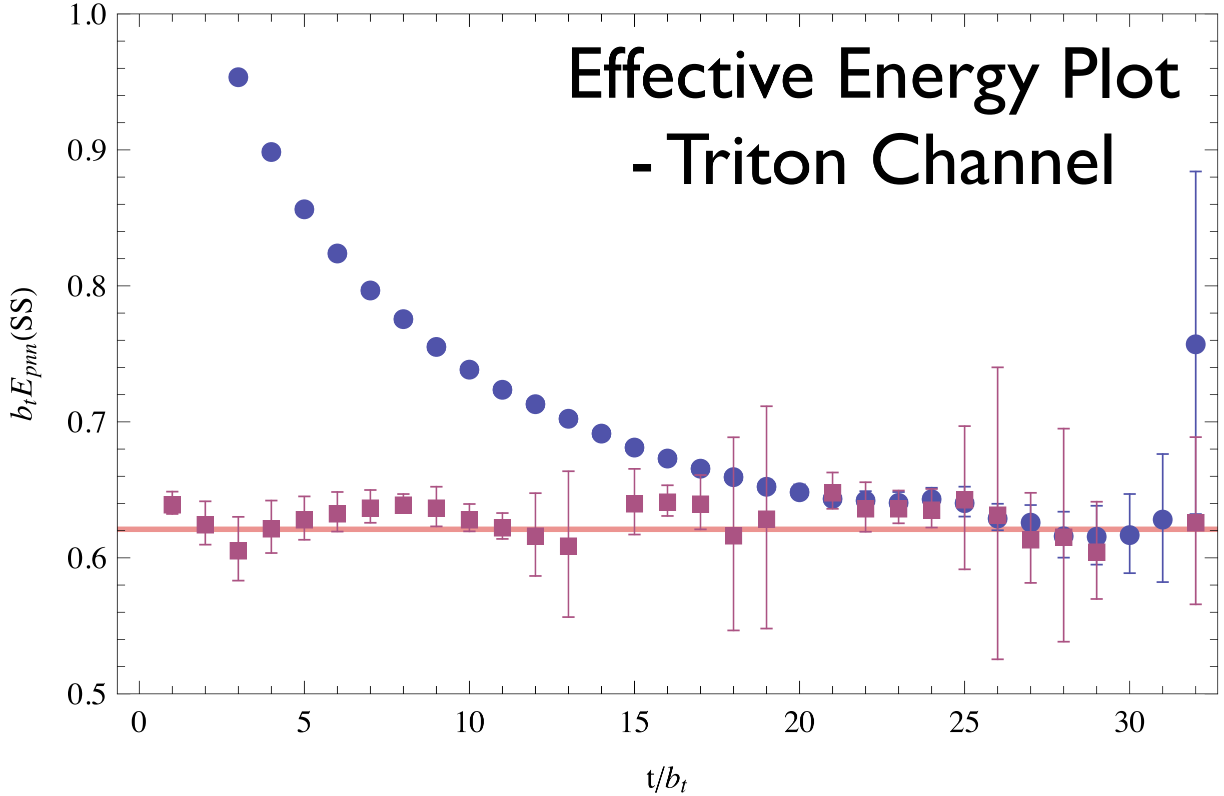


Publication : ArXive : 0905.0466

High Statistics Calculations on the Jefferson Lab Anisotropic Clover Lattices : Three Baryon Systems



High Statistics Calculations on the Jefferson Lab Anisotropic Clover Lattices : Three Baryon Systems : nnp



Interactions - Opportunities

- **Accomplishments**
  - Calculation of scattering lengths for rich range of hadron-hadron systems
  - First calculation of pion and kaon condensation
  - Developed powerful new methods for spectra
  - Successful calculation of 2 and 3 hadron systems
- **Challenges**
  - High-precision studies of baryon-baryon systems
  - Move toward calculation of light nuclei

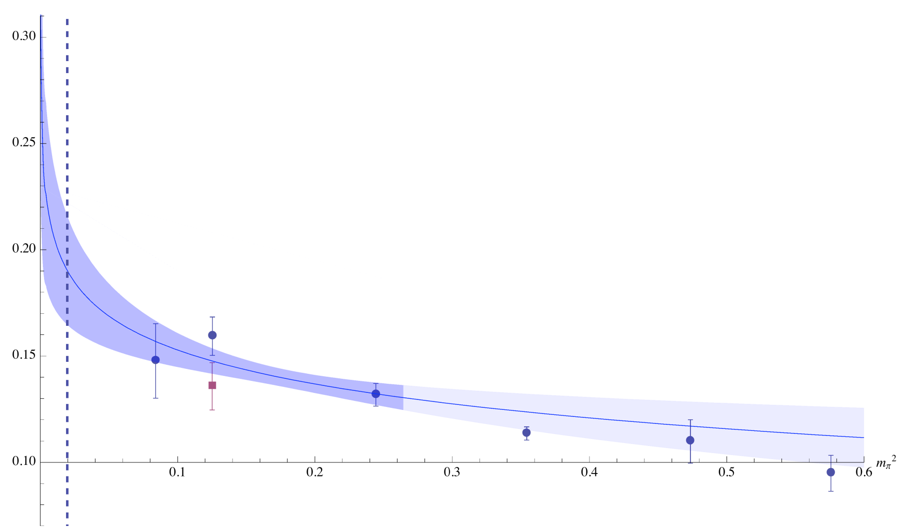
Summary

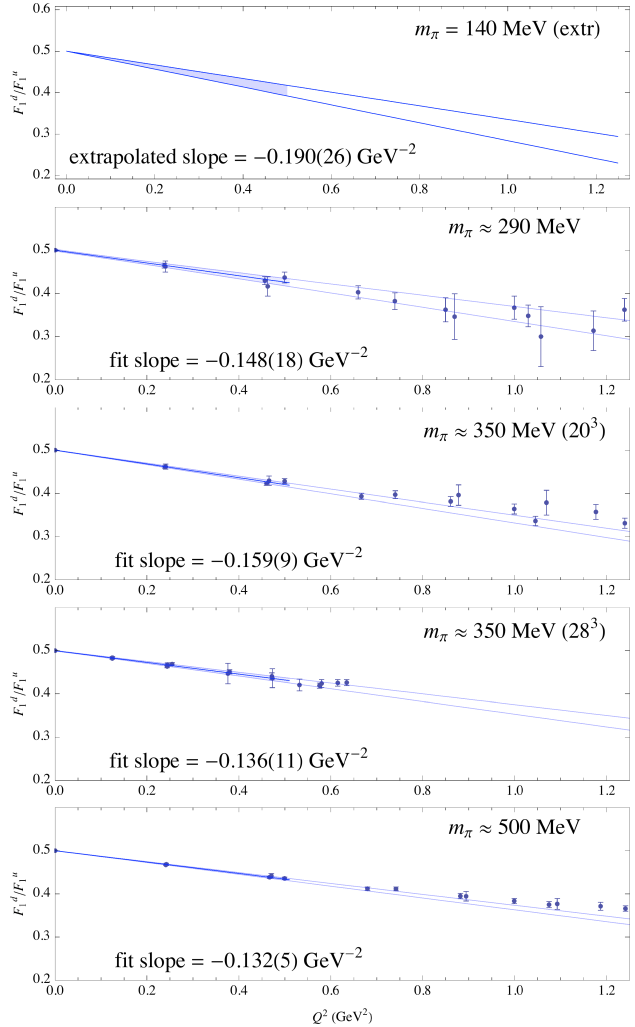
- Lattice QCD calculations essential to our understanding of hadronic physics, and to achieving the DOE nuclear-physics goals
- Dramatic algorithmic improvements are enabling us both to measure previously studied quantities to greater precision, and to exploit new opportunities
- Physics measurements, rather than gauge configuration generation, an increasingly computationally demanding part of the effort
- Increasing recognition of lattice QCD as essential tool for hadronic physics among both theory and experimental communities

Backup Slides

Synergy with Experiment

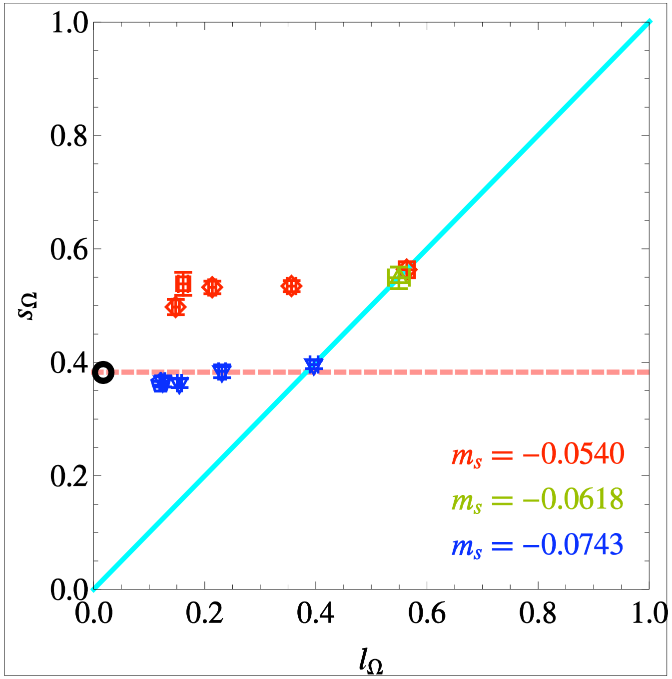
Timely Example:
Request for lattice comparison with
JLab E02-013 measurement of F_1^d / F_1^u



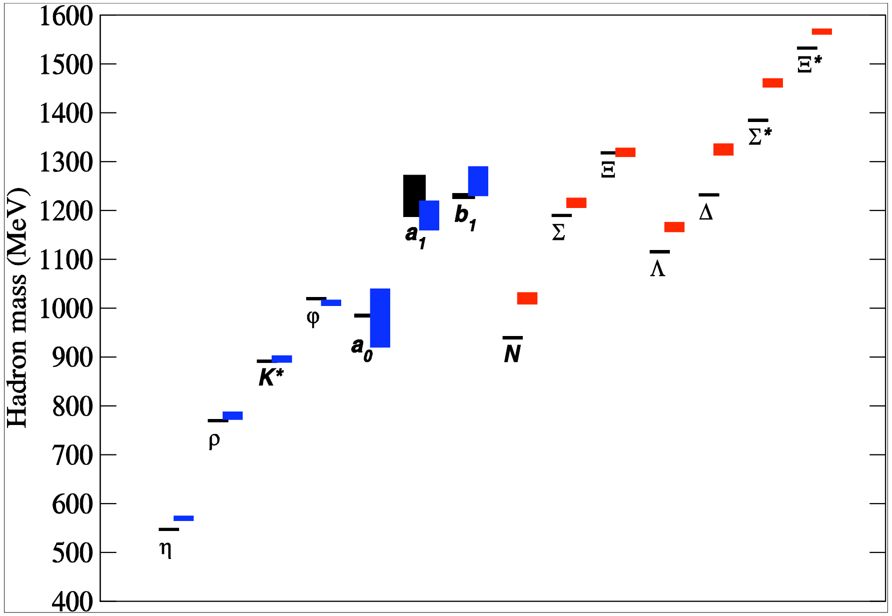


Anisotropic Clover Lattice Generation

- "Clover" Anisotropic lattices $a_t < a_s$*: major gauge generation program under INCITE and discretionary time at ORNL designed for spectroscopy*



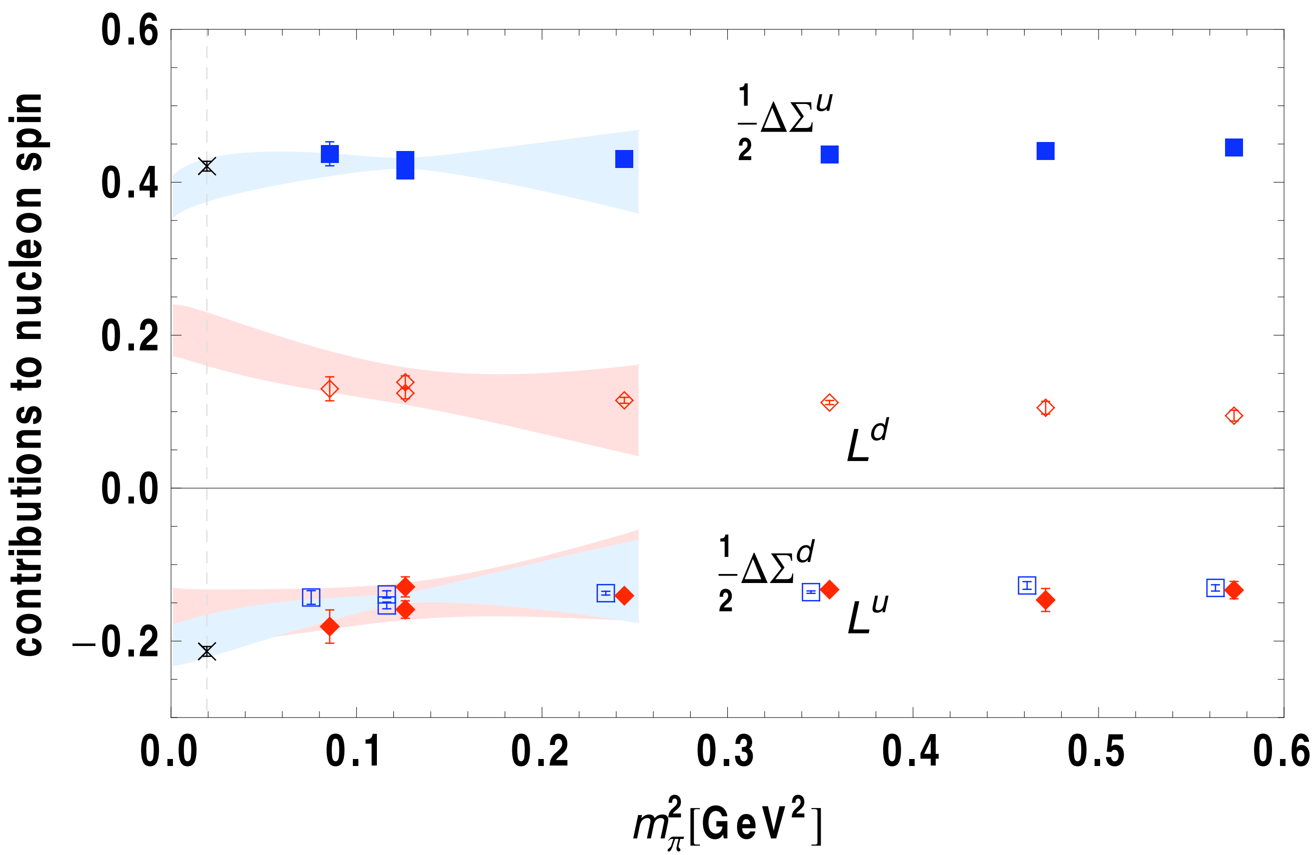
Novel way of specifying quark masses and scale



Low-lying hadron spectrum

H-W Lin et al (Hadron Spectrum Collaboration), PRD79, 034502 (2009)

Chiral extrapolation of the nucleon spin



Analysis of new high statistics data

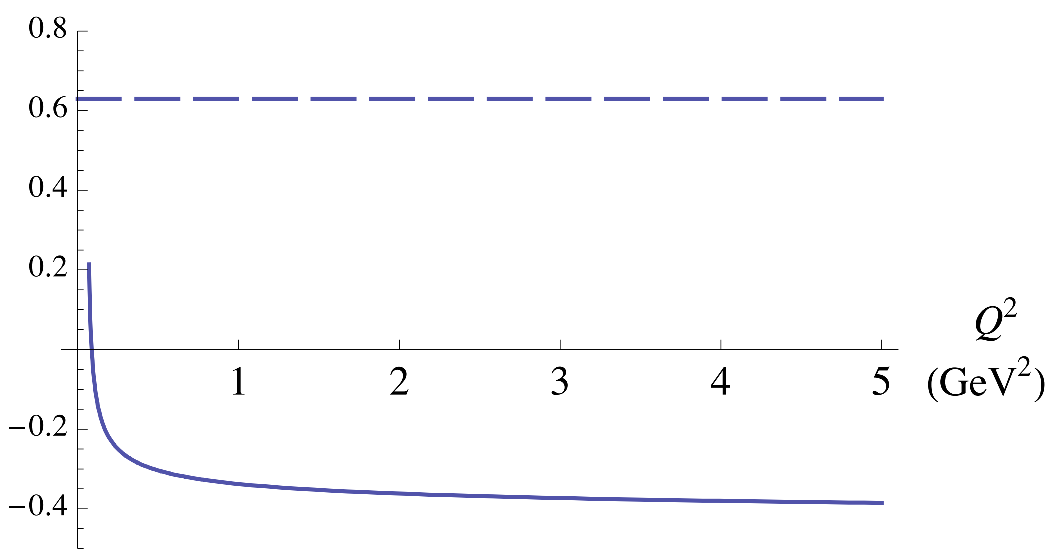
LHPC to be published

Evolution of nonsinglet angular momentum

Nonsinglet J has simple evolution A. W. Thomas arXiv:0803.2775 [hep-ph]

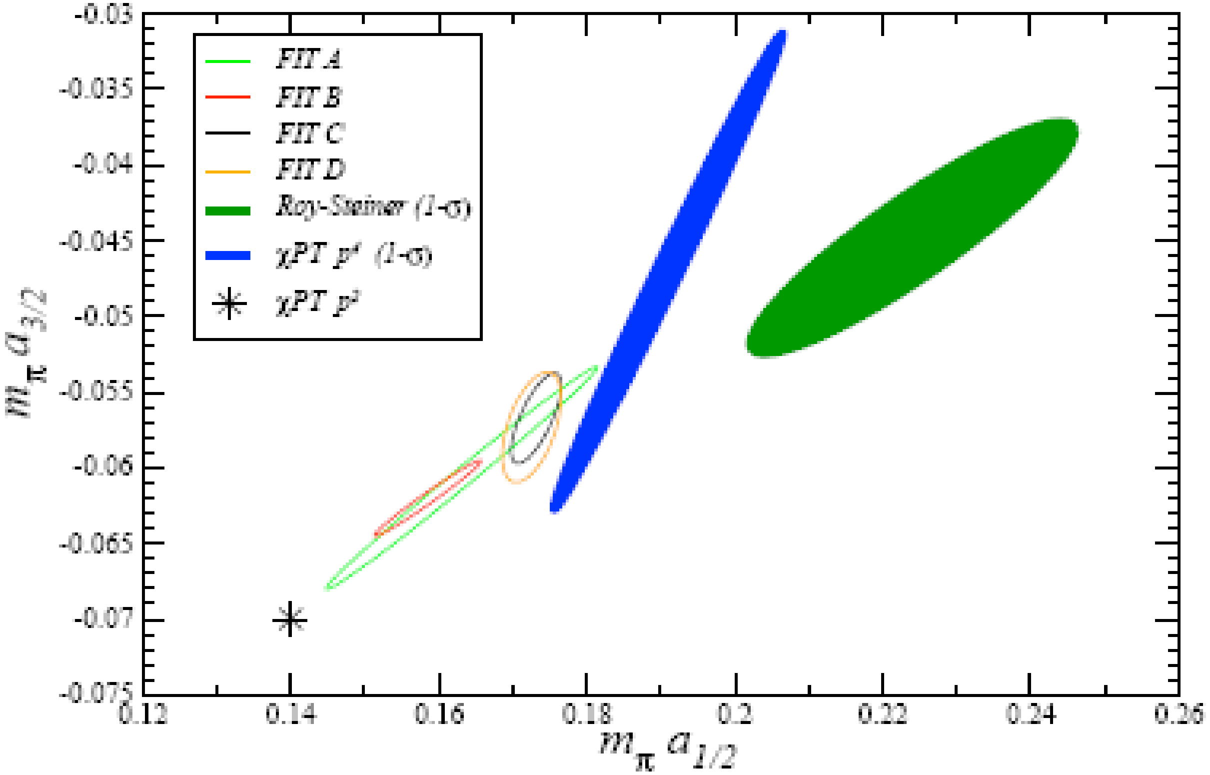
Spin conserved, so large change in L

$$L^{u-d}(t) + \frac{\Delta\Sigma^{u-d}}{2} = \left(\frac{t}{t_0}\right)^{-\frac{32}{81}} \left(L^{u-d}(t_0) + \frac{\Delta\Sigma^{u-d}}{2}\right) \qquad t = \ln\left(\frac{Q^2}{\Lambda^2_{QCD}}\right)$$



Meson-Meson Interactions - II

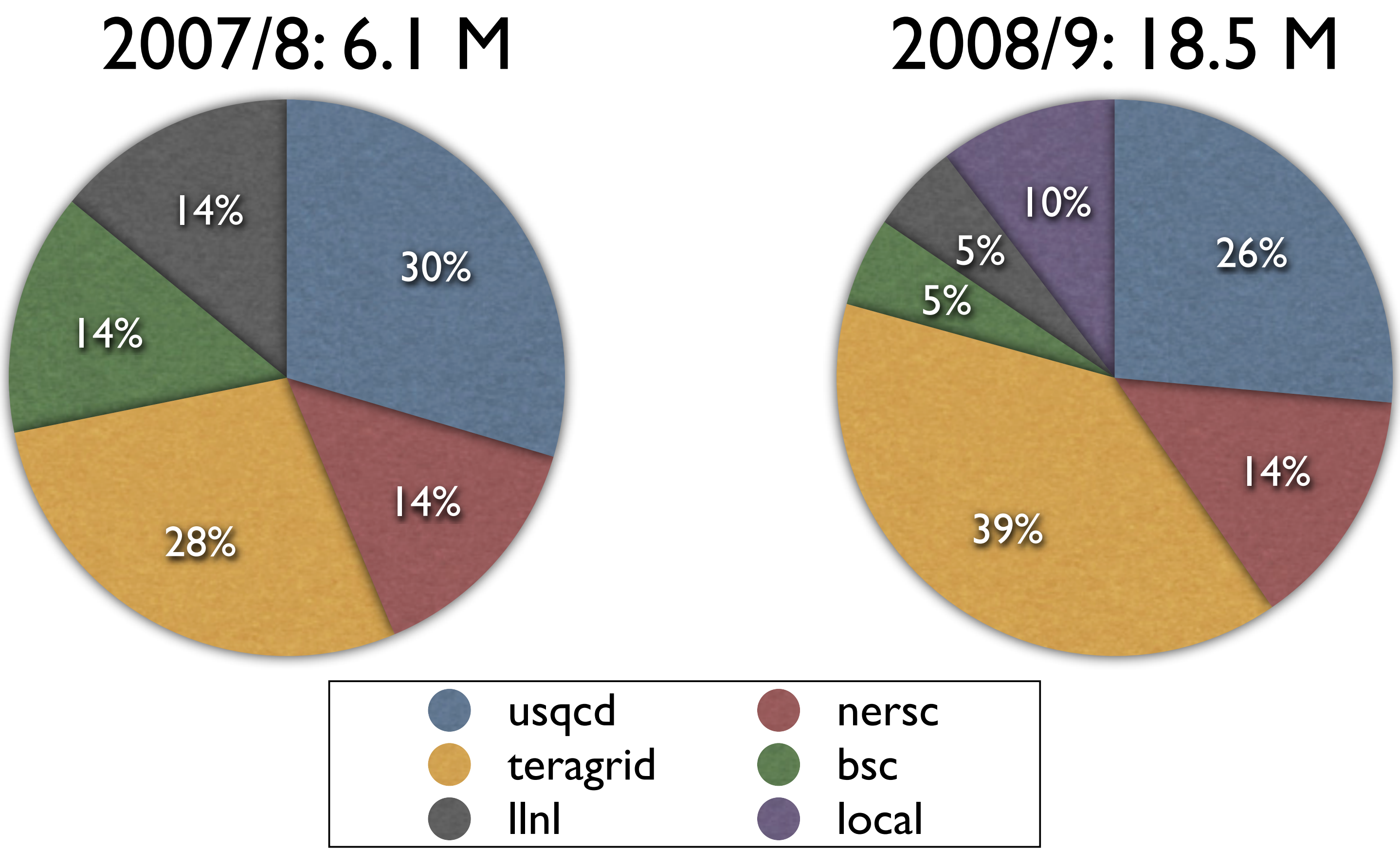
NPLQCD, Phys.Rev. D74 (2006) 114503



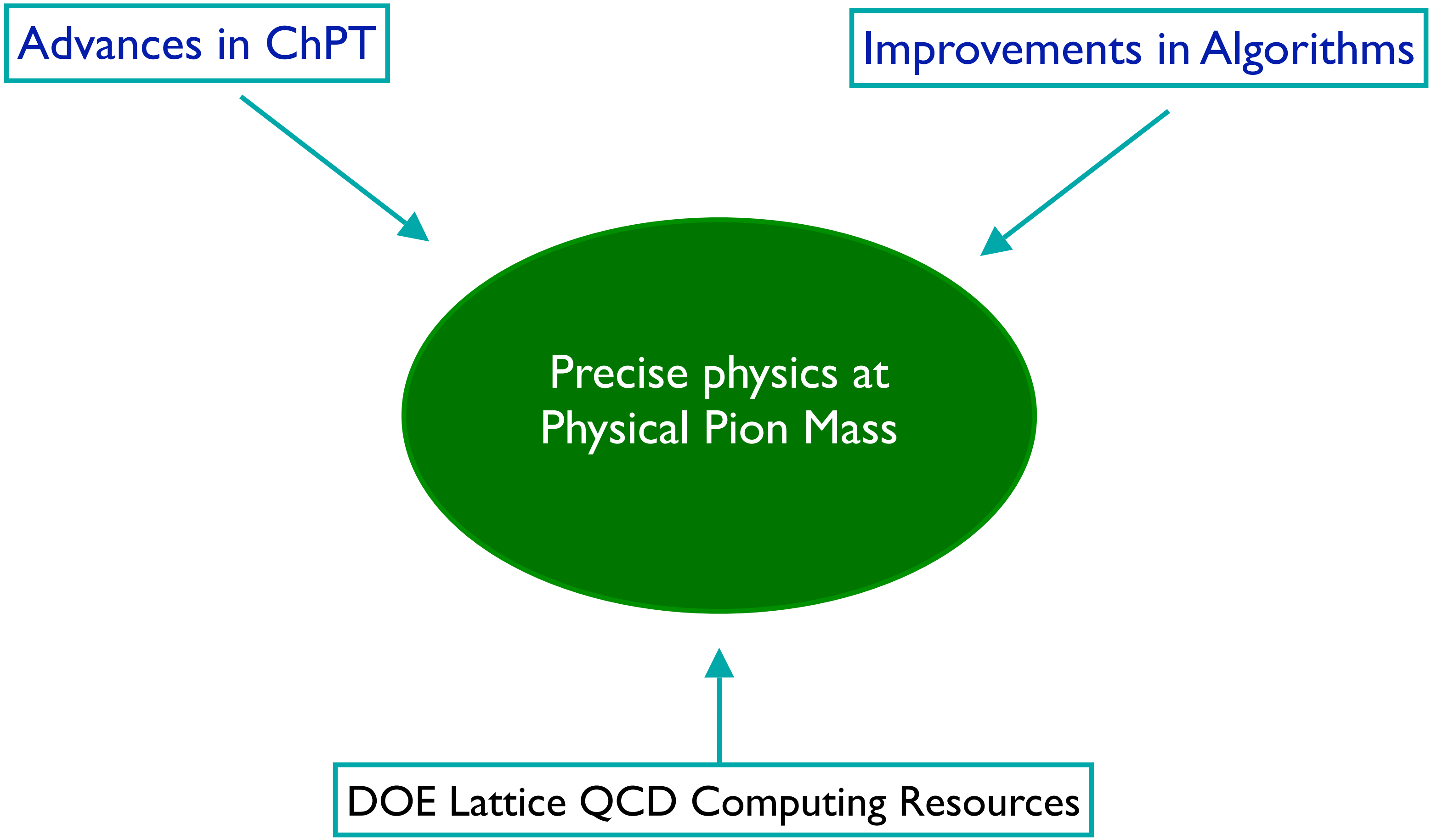
NPLQCD: Predictions for K π scattering lengths for both I = 3/2 and I = 1/2

NPLQCD Resources

6n node-hours



Summary


Advances in ChPT
Improvements in Algorithms
Precise physics at Physical Pion Mass
DOE Lattice QCD Computing Resources

Synergy with Experiment - II

Lattice QCD and Experiment: Revealing the Structure of Hadrons

search

print version

Synergy

Program - CEBAF Center, Meeting room F113

Friday, November 21, 2008

7:45 - 8:30	Registration/Continental Breakfast	
	Spectroscopy	
8:30 - 8:40	Welcome	Tony Thomas (JLab)
8:40 - 9:20	Status and Prospects for Meson Spectroscopy	Ryan Mitchell (Indiana)
9:20 - 10:10	Hadron Physics from Lattice QCD, and the Study of Meson Spectroscopy	Mike Peardon (Trinity College)
10:10 - 10:50	Status and Prospects for N* Spectroscopy	Volker Crede (FSU)
10:50 - 11:10	Coffee Break	
11:10 - 11:50	Lattice Studies of Baryon Resonances	Steve Wallace (Maryland)
11:50 - 12:30	Summary - Prospects for Spectroscopy	Frank Close (Oxford)
12:30 - 14:00	Lunch on own	
	Hadron Structure	
14:00 - 14:40	The experimental study of nucleon form factors	Ron Gilman (Rutgers)
14:40 - 15:20	Nucleon Form Factors on the Lattice	Meifeng Lin (MIT)
15:20 - 16:00	Coffee Break & Group Photo	
16:00 - 16:40	The phenomenology of Nucleon Form Factors	Hans-Werner Hammer (Bonn)
16:40 - 17:20	The transverse structure of hadrons	Matthias Burkardt (NMSU/JLab)
17:30	Reception and Dinner at CEBAF Center	

Saturday, November 22, 2008

8:00 - 8:30	Continental Breakfast	
8:30 - 9:10	Expt. Study of GPDs	Charles Hyde (Blaise Pascal/ODU)
9:10 - 9:50	Expt. Study of Transversity	Matthias Grosse-Perdekamp (Illinois)
9:50 - 10:30	Coffee Break	
10:30 - 11:10	Lattice studies of Hadron Structure	Gerrit Schierholz (DESY)
11:10 - 11:50	Expt. and Lattice: building a picture of the Nucleon	Anthony Thomas (JLab)
11:50 - 12:30	Roundtable	
12:30	Workshop adjourns	